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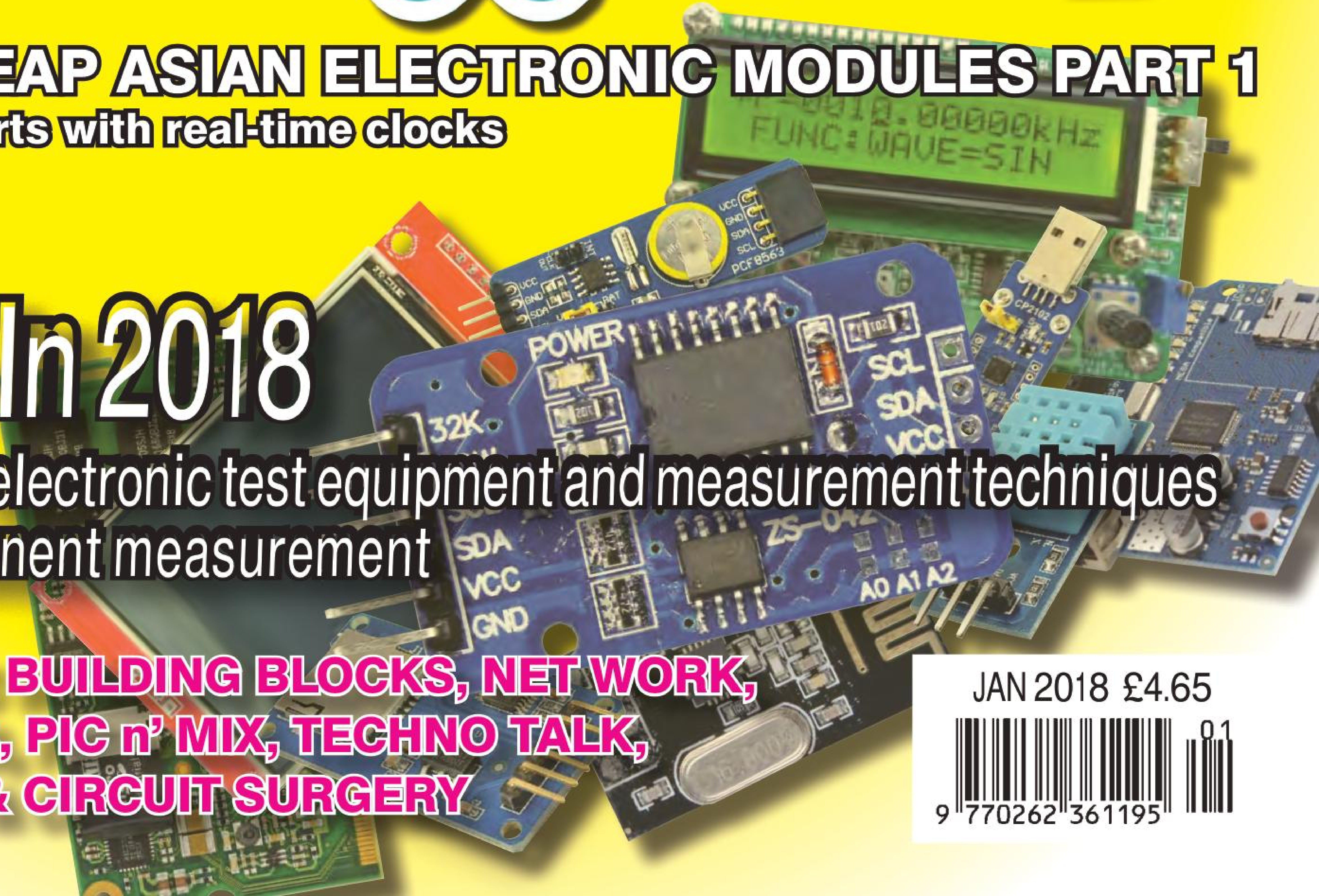
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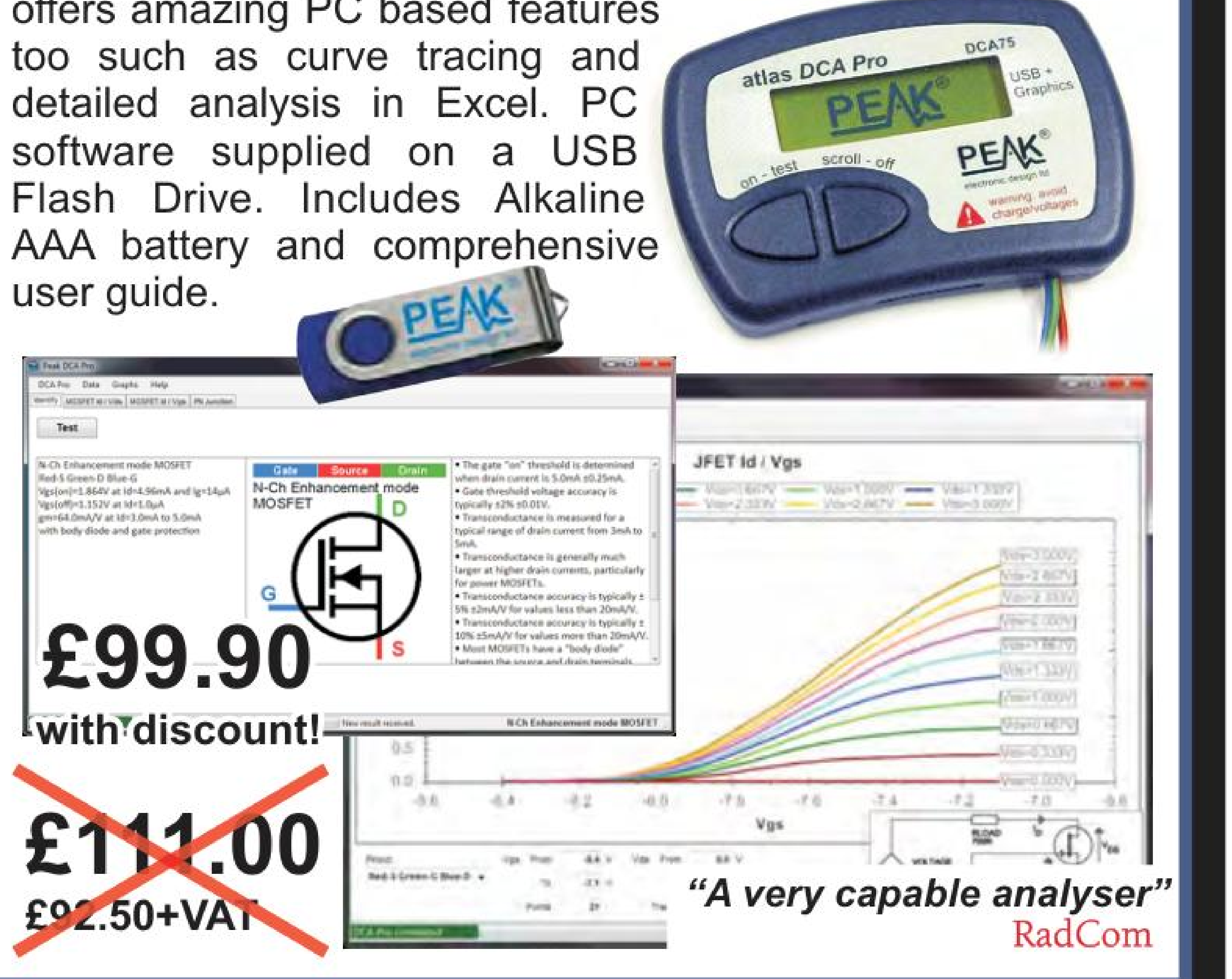
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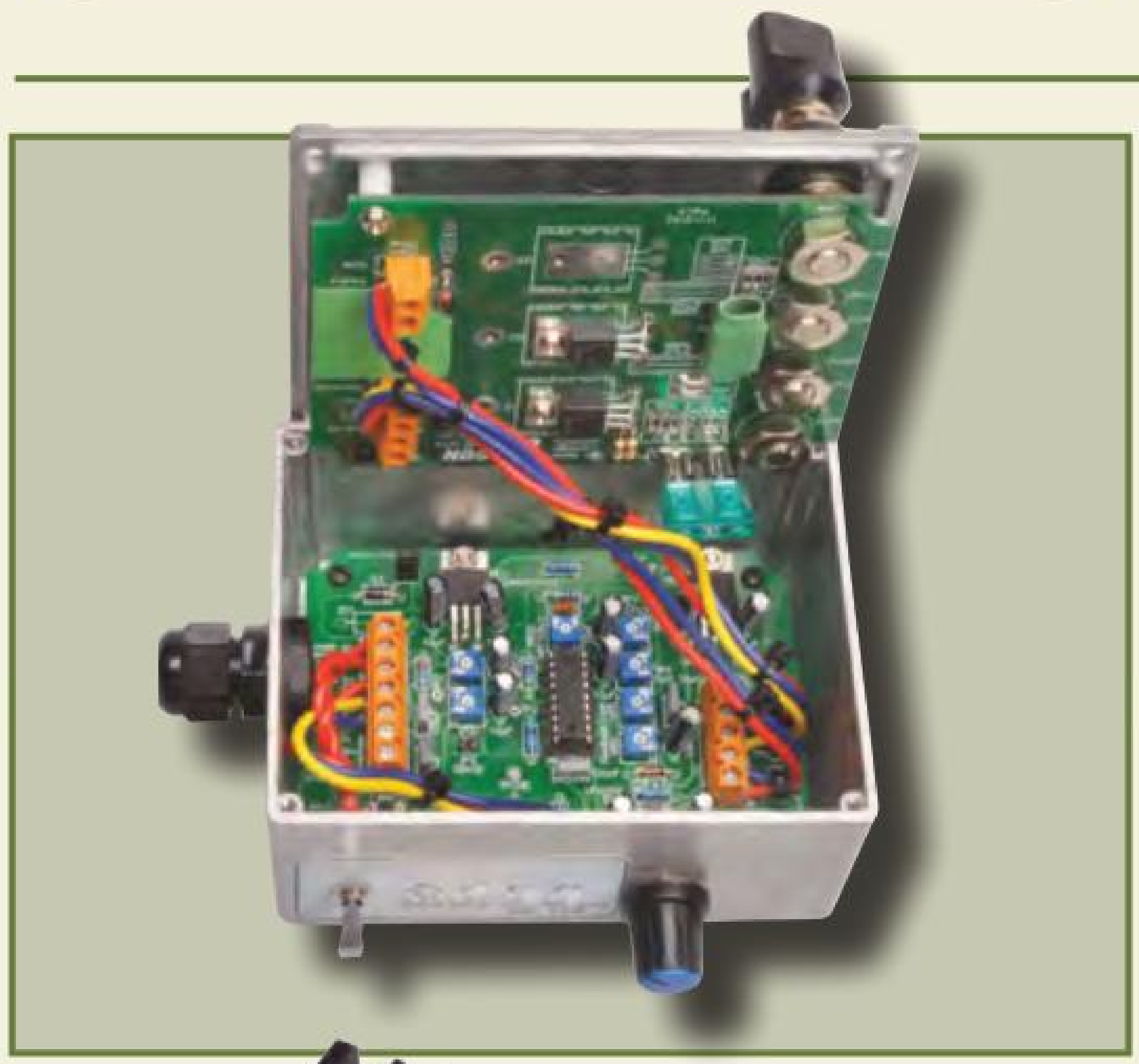

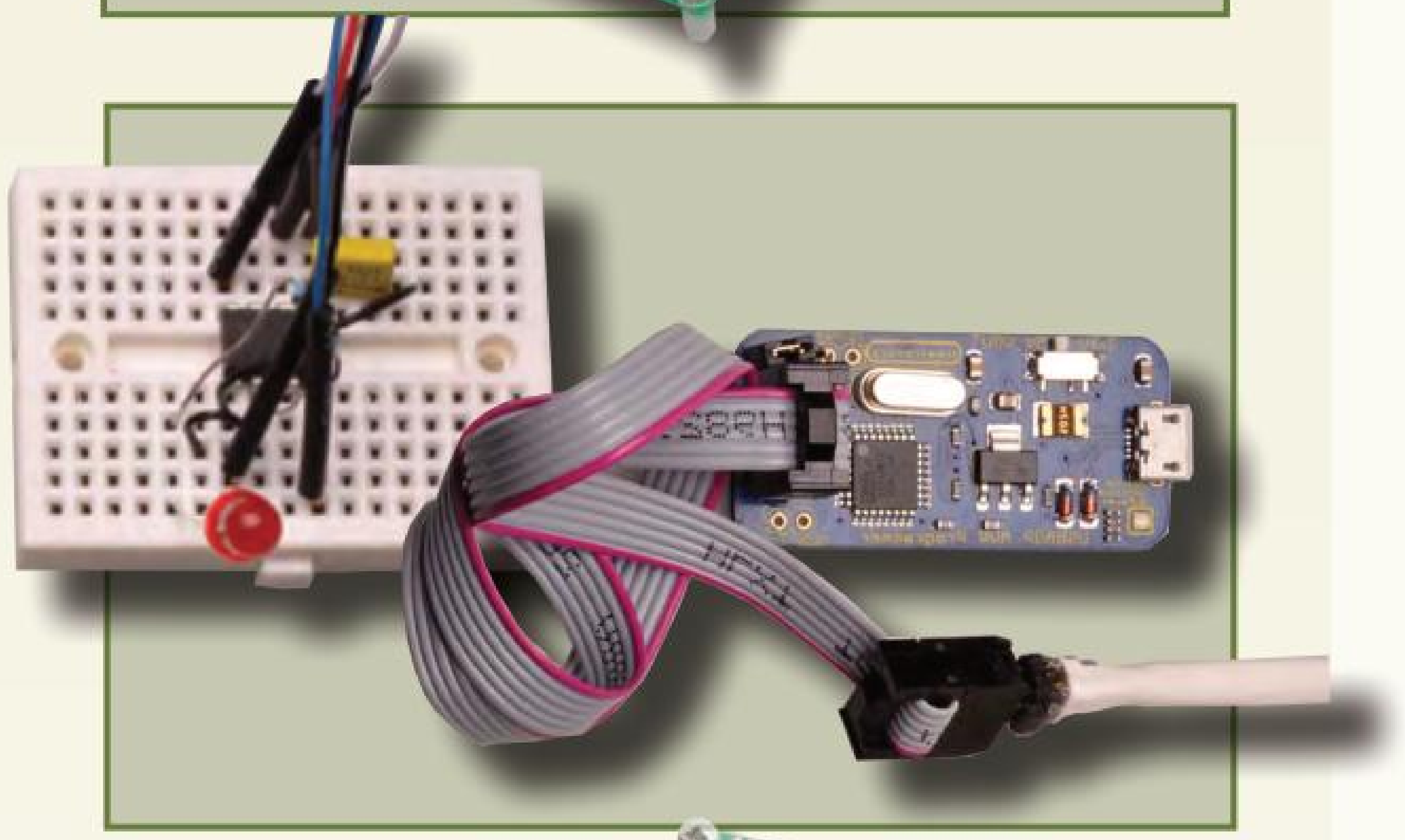

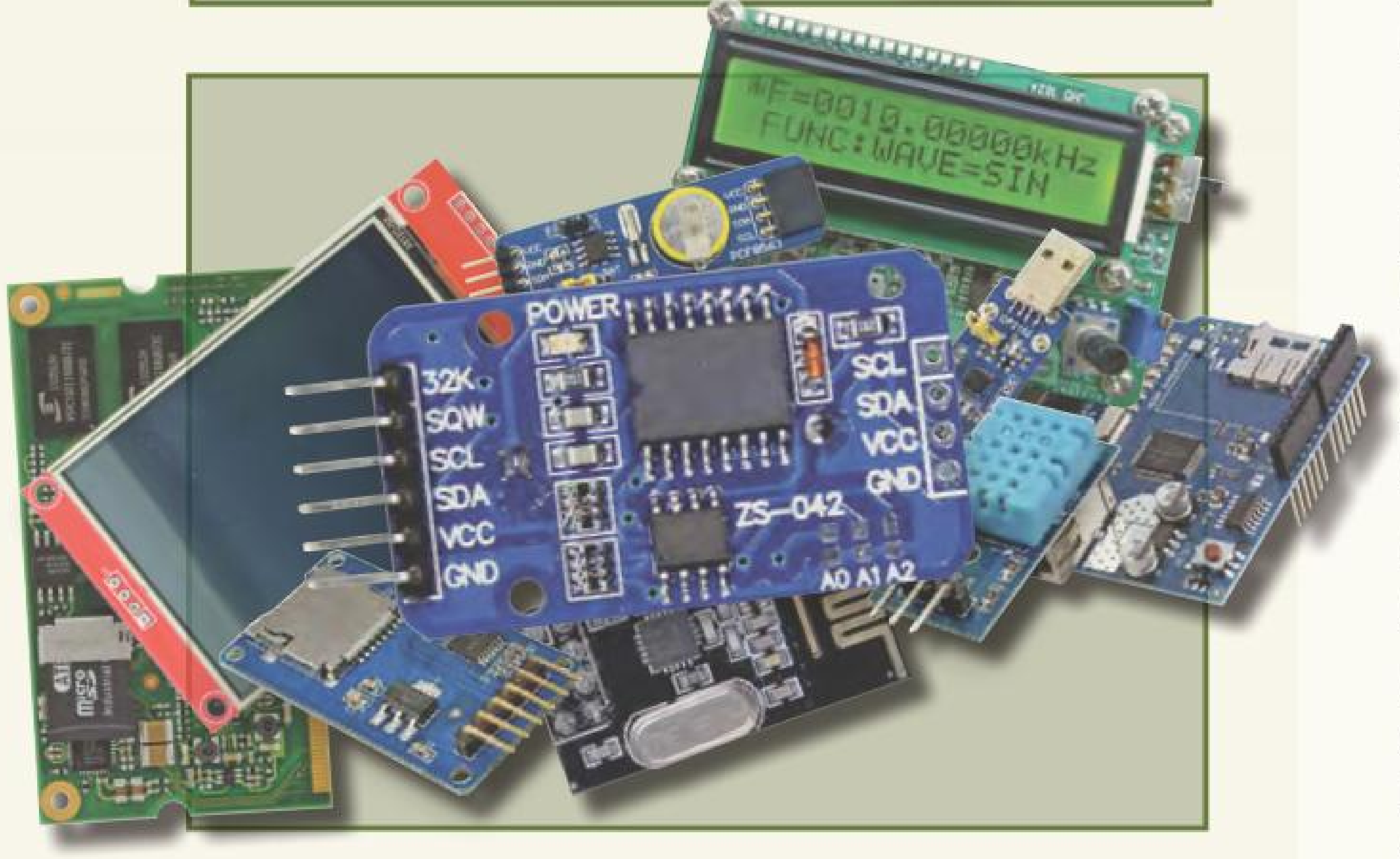

Projects and Circuits

HIGH-POWER DC MOTOR SPEED CONTROLLER – PART 1 12
by John Clarke
Powerful DC motor controller with cut-off, speed regulation and soft start

SC200 AMPLIFIER MODULE – PART 1 19
by Nicholas Vinen and Leo Simpson
Completely new amplifier circuit incorporating features of modern amplifiers, but using easy-to-solder through-hole components – no SMDs!

ARDUINO MEETS THE ATtiny85 MICROCONTROLLER 26
by Lawrence Billson
There are heaps of applications for Arduino boards, but what if you want to use one in your own design using the Atmel ATtiny85 microcontroller? Here's how!

USING CHEAP ASIAN ELECTRONIC MODULES – PART 1 34
by Jim Rowe
A new series to help you take advantage of handy pre-built electronic modules from Asia. In this article, we review the DS3231 real-time clock (RTC)

Series and Features

TECHNO TALK by Mark Nelson 11
Looking back, looking forward

TEACH-IN 2018 – GET TESTING! – ELECTRONIC TEST EQUIPMENT AND MEASUREMENT TECHNIQUES 38
Part 4: Component measurement

NET WORK by Alan Winstanley 48
Faster still... Flushed with success... Join us on EEWeb... Tag teams

PIC n' MIX by Mike O'Keeffe 50
Four-digit, seven-segment LED display – Part 2

CIRCUIT SURGERY by Ian Bell 54
Temperature sensors – Part 4

MAX'S COOL BEANS by Max The Magnificent 58
If it's Friday, it must be Sheffield… Bertie the Brain... Who's in control?... It's for you!

AUDIO OUT by Jake Rothman 60
Railing against convention – Part 1

ELECTRONIC BUILDING BLOCKS by Julian Edgar 68
LED VU Meter

Regulars and Services

SUBSCRIBE TO *EPE* and save money 4

***EPE* BACK ISSUES CD-ROM** 5

EDITORIAL 7
A welcome escape... Something for everyone!

NEWS – Barry Fox highlights technology's leading edge 8
Plus everyday news from the world of electronics

MICROCHIP READER OFFER 25
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***EPE* BACK ISSUES** 32

***EPE* TEACH-IN 8** 47

***EPE* TEACH-IN 7** 59

***EPE* CD ROMS FOR ELECTRONICS** 62
A wide range of CD-ROMs for hobbyists, students and engineers

DIRECT BOOK SERVICE 65
A wide range of technical books available by mail order, plus more CD-ROMs

***EPE* PCB SERVICE** 70
PCBs for *EPE* projects

ADVERTISERS INDEX 71

NEXT MONTH! – Highlights of next month's *EPE* 72

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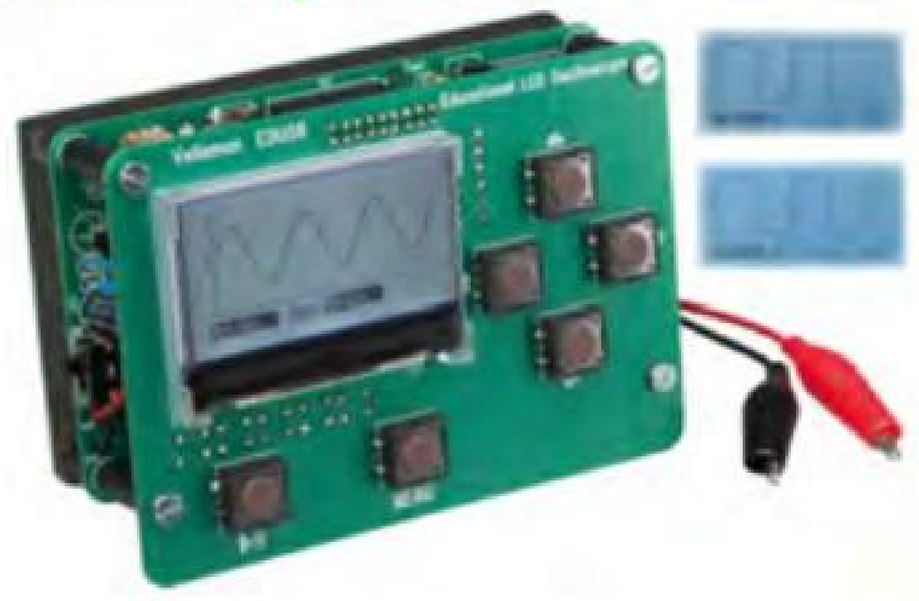

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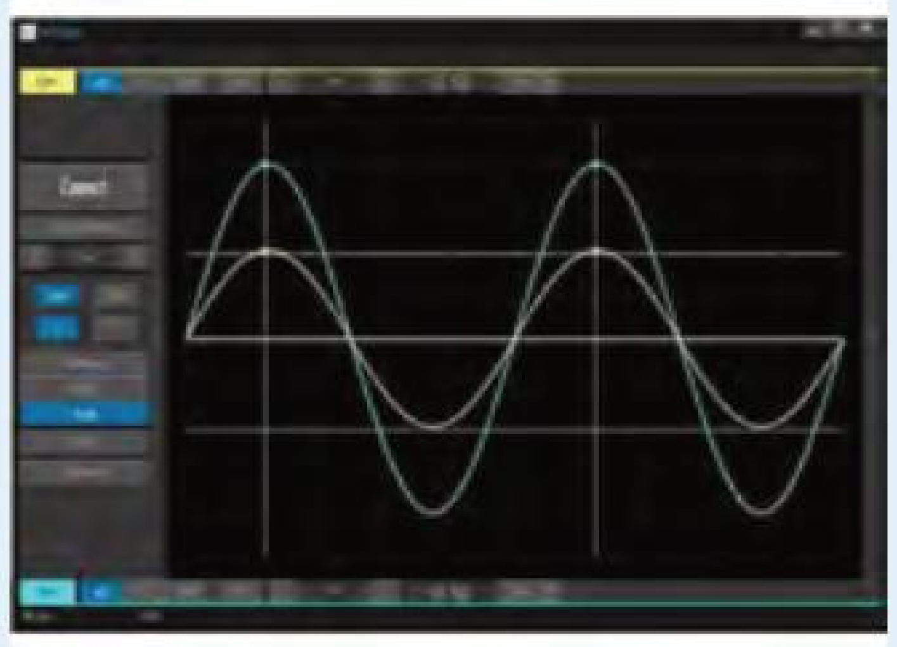

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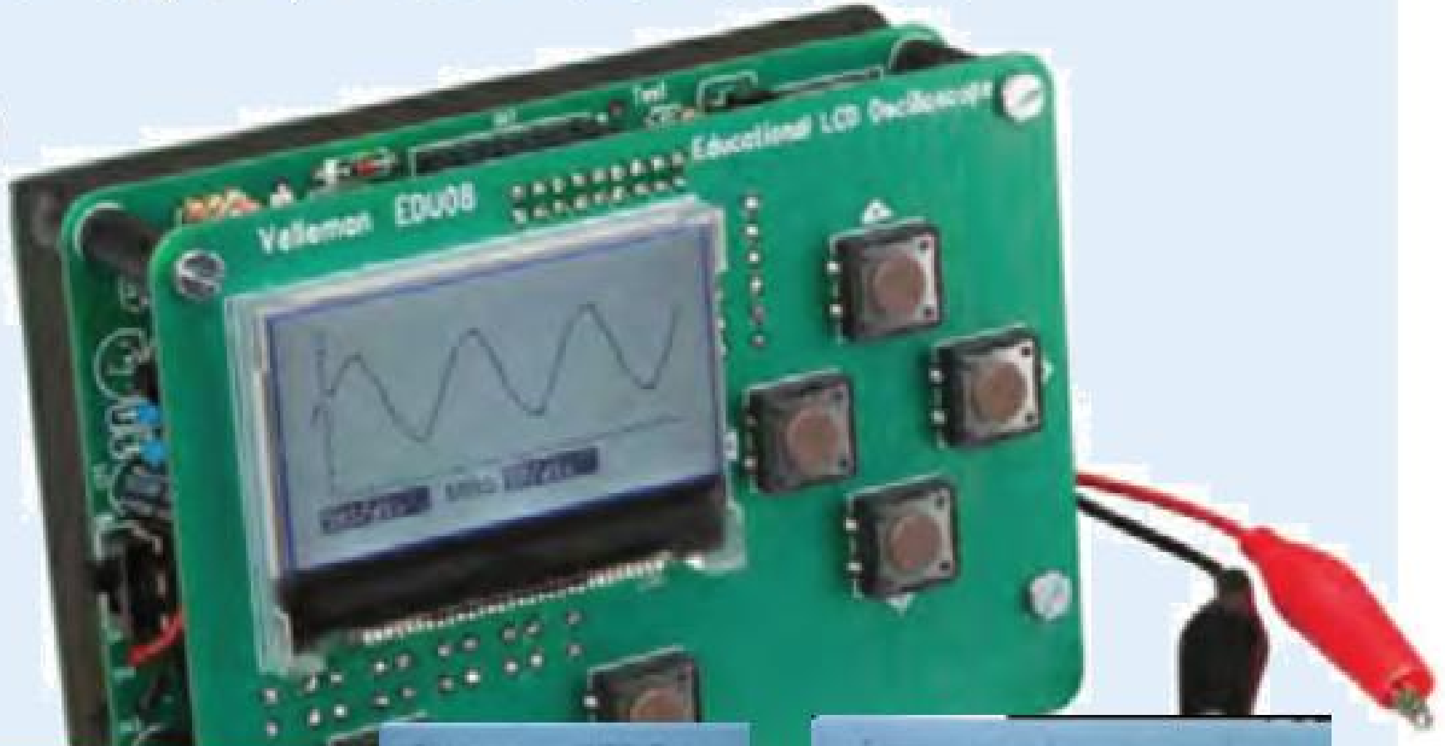

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EVERYDAY PRACTICAL ELECTRONICS

A welcome escape

We have a particularly enjoyable menu of projects and columns for you to read over the Christmas period as you digest your turkey, nut roast or whatever gastronomic indulgence you choose for the festive season. Boycott the brain (and soul) destroying march of reality TV, endless repeats and saccharine-loaded films, and settle down to read your favourite electronics magazine – better still, take up your trusty soldering iron and make something!

Something for everyone!

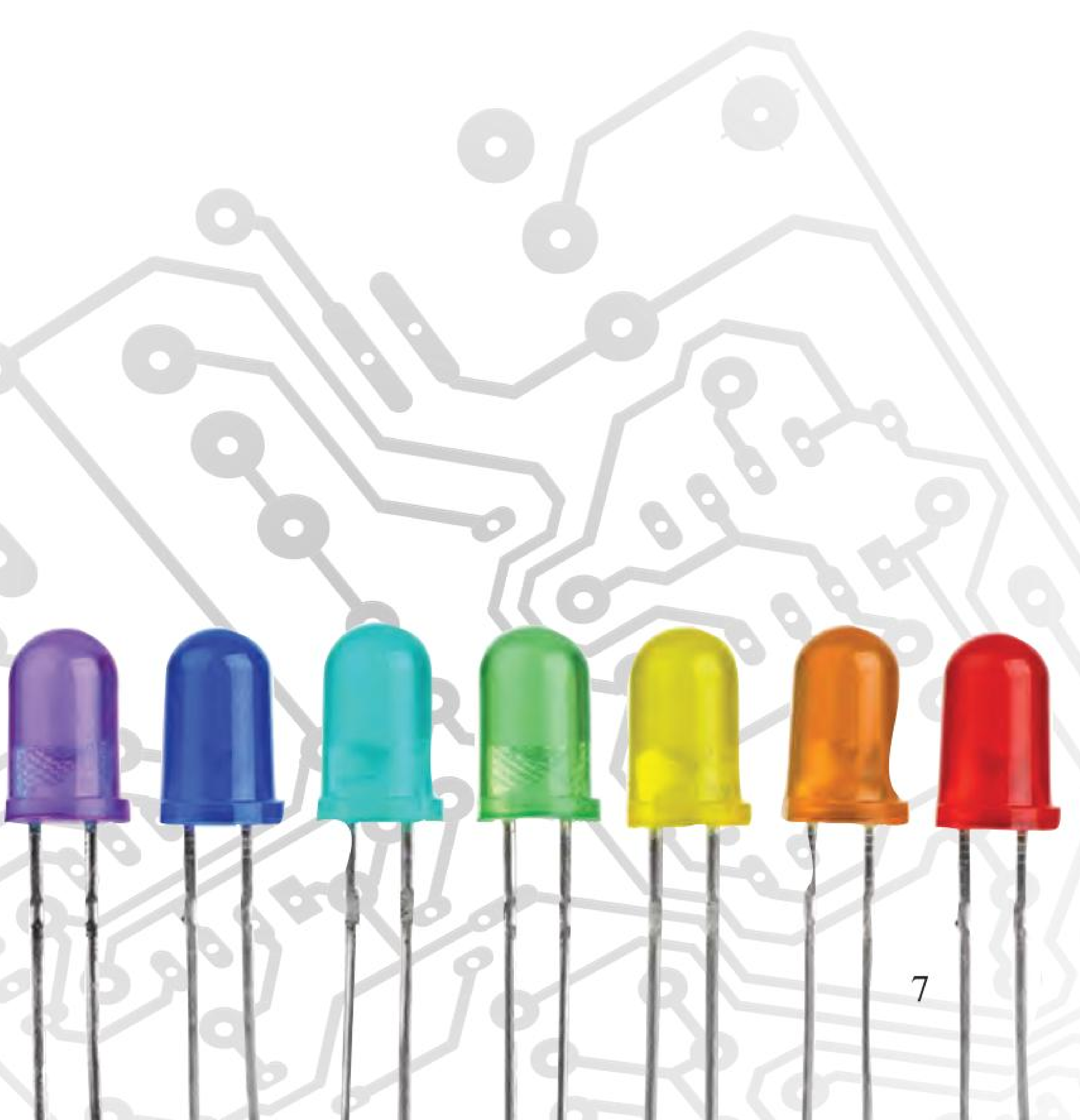
Is your amplifier struggling to do justice to Christmas carols? Then we have just the right project for you – the *SC200 Amplifier Module*. Its performance is outstanding and if SMD projects leave you cold, then fear not – there are no tiny surface-mount components in this design – just good old-fashioned through-hole devices.

Or, perhaps you fancy some real power behind your next control project? Our latest *High-power DC Motor Speed Controller* has bags of it, and will let you regulate some serious torque and speed.

If microcontrollers are your interest then you'll enjoy learning how to turn Arduino-based ideas into a design of your own using the Atmel ATtiny85 microcontroller. Believe it or not, it's actually quite easy – and cheap – opening a host of simple control projects and applications using just an 8-pin chip.

Last, but not least, we have a new series based around the rise of cheap, pre-built electronic modules regularly found on eBay and other websites. These ultra-low-priced Asian, often Chinese bargains typically cost less than you or I could hope to pay for half the included components, and they let you build and design systems with ease and efficiency. We kick off this month by looking at real-time clock (RTC) building blocks.

This issue contains all of the above and of course the regular delights of *Teach-In 2018*, *Circuit Surgery*, *Techno Talk* and much more – just what you need to have a thoroughly enjoyable break.



NEWS

A roundup of the latest Everyday News from the world of electronics

Berlin's eavesdropping spy tunnel – report *by Barry Fox*

Each year, I escape from the IFA showgrounds in Berlin to find out more about the once-divided city's fascinating history of East-West electro-espionage. This time, I visited the Allied Museum (**www.alliiertenmuseum.de/en**), housed in one of the theatre-cinemas built for the British and American troops who occupied the western half of Berlin, while the Russians occupied the eastern sector. The Allied Museum chronicles the 1948/9 airlift, when the Russians blockaded road, rail and river access to the West. Everything – including coal for electricity-generating power stations – as well as food and medical supplies had to be flown into Berlin along a narrow air corridor. The heavy transport aircraft flew round the clock into three West Berlin airports, one a minute for a full year.

The museum also has a seven-metre original section of a little known electronic spy tunnel. Like a corrugated metal worm, large enough for people to stand upright, this 450m tunnel was dug in the 1950s from the west under the east and tapped into the Russians' phone lines. A 19m chamber at the eastern end of the tunnel was packed with Ferrograph open-reel tape decks for recording Russian phone calls with East Berlin. British valve amplifiers avoided reduction in call level, which might have made the East suspicious.

5
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Cello has launched its new 'Platinum' range of UK-made television sets

Surviving section of the Berlin spy tunnel in the Allied Museum

Operation Gold

The project was called 'Operation Gold', and was organised by the US Central Intelligence Agency (CIA) and the British Secret Intelligence Service (SIS). The dig began in 1954, from under a phoney radar station built in the West, and ran under the heavily guarded East/West border to tap into three East Berlin telecoms cables. Although some teleprinter traffic was impenetrably encrypted, there was enough careless talk to keep a team of linguists in London busy transcribing useful secrets.

The irony is that British spy George Blake told the Russians about the tunnel while he was working for MI6 in the mid-1950s (before he was caught and jailed in 1961). It's not clear why his warnings were not heeded. One theory is that there was childish inter-departmental Moscow/Berlin rivalry; another is that the Russians needed to keep Blake's position as a mole inside the British security services secret. It's pure Le Carré stuff (**en.wikipedia.org/wiki/John_le_Carré**).

What is known is that after Blake moved departments inside the British security services, the Soviets 'discovered' the tunnel. In 1956, after the tunnel had been stealing secrets for a year, the Russians proudly displayed their find to the East Berlin press and public. Later, after the Berlin Wall came down, and the border zone was cleared of mines, a section of the decaying tunnel was dug up, preserved and put on display at the Allied Museum.

It's out in the Berlin suburbs, and a magnet for bus tours of Allied ex-servicemen. It's open to everyone, admission is free and reasonably easy to reach by subway and bus.

British-made TVs

After 15 years and two million sets, Cello (**celloelectronics.com**) the UK's only TV manufacturer is coming out from the B2B shadows with a new consumer range. The Platinum range includes Android Smart 4K sets with integrated sound bars, and is backed

Berlin's eavesdropping spy tunnel – *continued*

by a three-month, £0.5m consumer brand awareness campaign. This includes cinema adverts with all the UK's major chains, including Odeon, Cineworld and Vue. Platinum prices range up to £979 for a 65-inch set with six-speaker bar.

Speaking at the Platinum range launch, held aboard historic British warship HMS Belfast moored on the River Thames in London, Brian Palmer, Cello Electronics CEO, told us: 'We now have 50,000 square feet with two assembly lines, warehouse and office space in Bishop Auckland, County Durham. We did try selling through supermarkets, but found it a dangerous business to be in, and pulled out. They were sending returns in bin bags. So now we sell by mail order and through independent distributors like Euronics (under the old Ferguson name), TV Village, Appliances Direct and CIH. We buy our displays from all the usual sources, Samsung, LG and China, to keep control on the prices. There's not much difference in how they perform.'

Palmer says Cello has also been doing good business in African states Tanzania, Kenya and Rwanda, with a range of Digital TVs that have inbuilt Li-ion batteries and come with a 30W solar panel for 10-hour playing time. The TVs can also power an LED light and charge a mobile phone.

'There is digital TV to receive there, but 80% of the country has no grid power', he told us. 'These solar battery sets are also popular with British lorry drivers. They can watch TV at night and not find their vehicle battery is flat in the morning, which would mean they couldn't start the engine. They then recharge during the day'.

Palmer also confided that all the UK's prison population are watching TV on sets made by Cello, albeit not labelled. The sets, and even the remote controls, are transparent so that nothing can be hidden inside. The control software is modified, too, so that the prison authorities can control what channels the prisoners watch.

IBM aims for 50 qubits

An IBM cryostat wired for a 50-qubit system.

IBM has announced two significant quantum processor upgrades for its IBM Q early-access commercial systems, an initiative to build commercially available universal quantum computers for business and science. While technologies like AI can find patterns buried in vast amounts of existing data, quantum computers will deliver solutions to important problems where patterns cannot be found and the number of possibilities that you need to explore to get to the answer are too enormous ever to be processed by classical computers.

The first IBM Q systems available online to users will have a 20-qubit processor, featuring improvements in superconducting qubit design, connectivity and packaging. Coherence times (the amount of time available to perform quantum computations) will have an average value of 90µs, and allow high-fidelity quantum operations.

IBM has also successfully built an operational prototype 50-qubit processor with similar performance metrics. This new processor expands upon the 20-qubit architecture and will be made available in the next generation of IBM Q systems.

The latest hardware is a result of three generations of development since IBM first launched a working quantum computer online for anyone to freely access in May 2016. Within 18 months, IBM brought online a 5 and 16-qubit system for public access through IBM Q and developed the world's most advanced public quantum computing ecosystem. So far, over 60,000 users worldwide have run 1.7 million quantum experiments.

Arduino IoT in the Cloud

Arduino has released a rich set of new features for its Create Cloud platform (**create.arduino.cc**) aimed at expanding the number of Arduino-supported platforms for the development of IoT applications. Create Cloud users can now program Linux boards as if they were regular Arduino boards. Multiple Arduino programs can run simultaneously on a Linux-based board and programs can communicate with each other.

To further simplify design, Arduino has also developed a novel out-of-the-box approach, which enables anybody to set up a new device from scratch from the Cloud without any previous knowledge by following an intuitive web-based wizard.

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TechnoTalk

Looking back, looking forward

Mark Nelson

The above is a traditional topic for January commentaries, so why should I buck the trend? Relax while you read how our electronics hobby has changed – and hasn't changed – over the past sixty years.

OLD TIMERS (PEOPLE EVEN OLDER than me) sometimes wax lyrical about the early 1950s, when electronics was an affordable pastime – and one that earned you admiration from others. Ah yes, those were the days!

The good old days?

So what made them a golden era? For a start, being involved in hobby electronics in those days marked you out as a very clever and important person. Electronics was seen as a highly technical specialism and everybody had at least a vague notion of how 'boffins' had made a major contribution to the Allied victory with their work on radar, avionics and all manner of other electronic wizardry (this was before anyone had even heard of Enigma and Bletchley Park). If you could mend your neighbour's wireless set (or even fix his wife's vacuum cleaner) you too were one of those revered experts.

In those days there were no magazines dedicated to the electronics hobby but, *Practical Wireless* and *Wireless World* included plenty of articles on general electronics. Even better, their back pages were jam-packed with advertisements for all manner of government/war-surplus equipment for sale at bargain prices. You could buy radio receivers, transmitters, bomb release switches from aircraft, rotary converters, weird modules and heaven knows what else. Mail order was an option, but in those days many large towns had shops dedicated to a myriad of electrical and electronic 'junk'.

Make do and mend

Most of the items offered for sale had no direct use whatsoever – but they were ideal for disassembling. This way you could amass aluminium chassis, tag boards, fuse holders, panel lamps, switches, valve holders, passive components and goodness knows what else for (old) pence. All you had to do was carry the stuff home on the bus, ignoring the strange looks, and spend a happy evening or two desoldering the components, fortified with a steaming mug of Bovril. Every nut, bolt and washer was saved in screw-top glass jars, while the other components were stashed in cardboard boxes.

In those days, only a few folk could afford a television, although a number of people had a TV aerial installed to fool their neighbours into thinking they did have a telly. Taking the coronation year of 1953, the average weekly wage was £9 on which you paid 45% basic income tax (and had to work around 45 hours). This meant that a cheap television receiver (9-inch black and white screen, with just 405 lines of screen resolution) cost the equivalent of five weeks' wages.

Hero worship

Some electronic hobbyists became local legends by building their own TV set. Several publishers produced paperback booklets providing step-by-step instructions on how to convert a war surplus radar display into a (fairly) cheap television receiver. This was ideal if you didn't mind watching a green circular picture and could put up with terrific 'vision lag' that smeared your view of fast-moving images. People managed to put up with these shortcomings and basked in glory when friends and neighbours came round to watch the miracle of television after supper.

In those days, television, radio and Lo-Fi (there was little Hi-Fi back then) were considered luxuries by successive Chancellors of the Exchequer, and were fair game for raising taxes. You paid the dreaded purchase tax of 5% on the wooden cabinet (because it was furniture, hence, 'a good thing') but 50% on the innards (because they were a luxury). I'm told that the levels of purchase tax were reduced just before the coronation, so everyone rushed out and bought their first TV, creating a bonanza for the consumer electronics industry.

Back to the future

Things are different now, but practical electronics hobbyists are enjoying another golden era, thanks to the glut of low-cost components imported from the Far East. I have no idea how long this situation will last, but right now could be a good time to stock up on things that you might need in the future, however sore your wallet may be feeling. In that connection, it's probably daft to suggest you might have any money left following Christmas, but you might treat the following purchase suggestion as a need-to-buy item rather than an act of gross self-indulgence. (And if not that, then something to put on your wish list.)

If you cast a glance at the websites of professional electronics distributors you will see a category of goods called 'production aids', or more prosaically 'tools and equipment'. This is where you will find high-end soldering stations, purpose-made PCB etching baths, flow-soldering ovens and suchlike. Normally, I let my eyes glaze over at the sight of all this expensive equipment, but recently I discovered a gem of a product at a fairly affordable price and it might just interest you. I'm certainly pleased with the one that I have bought.

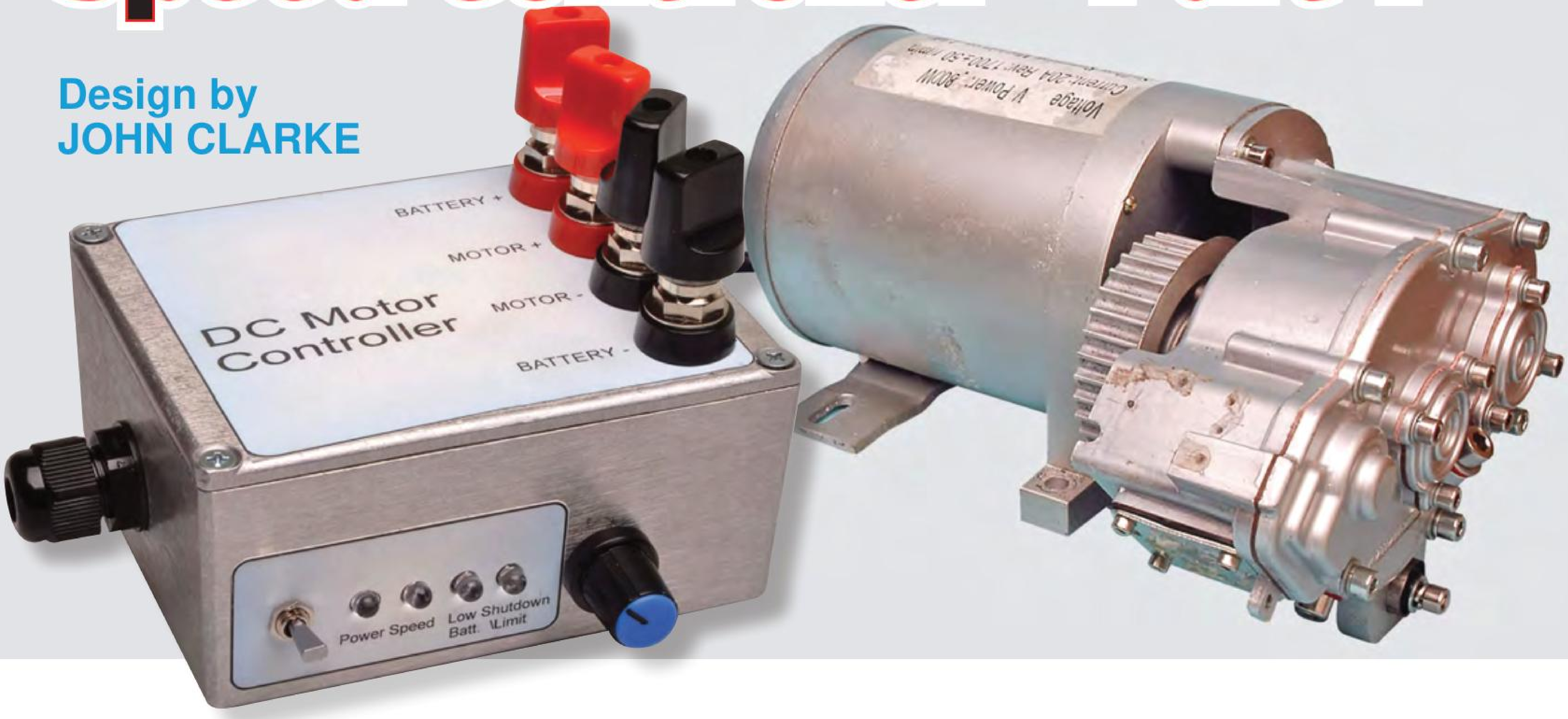
Absolute boon

For normal folk, populating a PCB with components and soldering them in place before they drop out of their holes can be a bit of a pain. At times like this you need four hands and asbestos fingers – and the forbearance of a saint. But not any longer, which is why I commend to you the Weller ESF 120 soldering stand. Because a picture is worth a hundred words and a video is a thousand of them, I suggest you take a peep at: **https://youtu.be/NMLoXg-yBe**s

In a nutshell it's a device that holds a PCB in mid-air while you plant each component, with a devilishly clever cushioned arm that prevents the component from dropping out when you turn the board over to solder it in. The adjustable grips can hold PCBs of any size up to double Eurocard size (160 x 235mm) and the board can be rotated through 360 degrees for adjusting and locking the board at the angle you require. As the manufacturer says, it is ideal for assembling prototypes and small production batches. I say it's an absolute boon. The price varies widely – so do shop around – but I found it for £49 at Farnell (order code 2292007).

High-Power DC Motor Speed Controller - Part 1

Design by
JOHN CLARKE



So you need a speed controller for a powerful DC motor. How much grunt do you want? This design has bags of it and can run with a DC supply from 12V to 60V, at currents up to 40A. Plus, it has low-battery cut-off, speed regulation (feedback), soft start and other useful features.

The 24V/20A speed controller published in our June 2011 issue has been extremely popular and reliable over the years, and it is still a valid design if you want a fairly modest power output. But now we have come up with a new design which can be regarded as our June 2011 design on steroids.

Not only will it work with much higher battery voltages, up to 60V (equivalent to a 48V lead-acid battery) and at currents up to 40A, it has a wide range of features which will make it much more flexible.

What sort of motors can you use with this *DC Motor Speed Controller*? Answer: any brushed DC motor; permanent magnet, series-wound or shunt-wound – and with current ratings up to 40A.

Features

One drawback of all our past DC speed controllers is that one side of the motor needs to be tied to the positive side of the battery. This is a problem in car applications because in those cases, one side of the motor is tied to chassis. Our new design caters for either situation, depending on link options on the PCB. It provides good speed regulation as it monitors the motor back-EMF. (Back-EMF is the voltage generated by the motor which opposes the current flow.)

Motor back-EMF increases in proportion to the motor speed and so it can be used to provide good speed regulation.

Soft start is another desirable feature, which means that the motor does not start with a sudden jerk as soon as power is applied. Instead, it can be programmed to start very gently or very rapidly, depending on the setting of a trimpot.

The speed of the motor can be adjusted using a standard potentiometer (ie, via a rotary knob) or via a twist-grip (Hall effect) throttle, as on electric bikes. There is also a flashing LED which gives a visible indication of the speed setting, with short flashes meaning low speed and longer flashes indicating high speed.

Maximum speed setting

Often, you need to limit the speed at which a motor can run and in this design it is simple to set.

As with our other DC speed controllers, this circuit works on the pulse-width modulation (PWM) principle, which means that it controls the power by rapidly switching two or three paralleled MOSFETs on and off.

And since PWM speed controllers can result in an audible whine from the motor, we provide a trimpot to adjust the PWM frequency so you can tune it to minimise audibility of the switching.

We should also state that some motors will work better at low PWM rates since they may have high inductance.

Others may work well at higher frequencies, but the switching noise becomes more audible. Hence, setting the PWM frequency is a compromise for the particular motor you are using.

Emergency stop

This feature is self-explanatory. Hit a switch and motor will stop immediately. If you don't need it, you can leave the switch out.

Emergency stop operates in one of two modes. The first will restore normal operation once the throttle is returned to zero. The second will only restore normal operation when power is switched off and then on again.

Finally, to prevent the battery being discharged too deeply and causing permanent damage, there is a low battery cut-off trimpot. For example, with a 12V battery, you might have a cut-off setting at 11.5V. Going below that with sealed lead-acid (SLA) batteries can cause battery failure.

Two PCBs

The *DC Motor Speed Controller* is mounted in a compact diecast aluminium case with four high-current binding post terminals, two for the battery connections and two for the connections to the motor.

On the side of the box are four LEDs, to indicate Power, Speed, Low Battery and Shutdown/Limit. There is also a toggle power switch and the speed control knob.

Inside the box are two PCBs, one sitting on the base and one attached to the lid.

The PCB on the base is the control board, carrying the microcontroller and the eight trimpots, and this is linked to the lid-mounted switching PCB which has the fuseholder, MOSFETs and the four binding post terminals.

High-side and low-side switching

We have already mentioned that this circuit can work with one side of the motor tied to the positive side of the battery and it will also work with one side of the motor tied to the negative side of the battery, which is the case with most, if not all the DC motors used in cars.

Where the motor is connected to the positive side of the battery, the MOSFET doing the PWM switching is connected between the negative terminal of the motor and the negative terminal of the battery. We refer to this as 'low-side switching' and this is depicted in the circuit of Fig.1(a). (This configuration has been used in most of our previous DC motor speed controllers.)

Features

- Operation up to 60V at currents up to 40A
- High or low-side switching
- Hall-effect or potentiometer throttle
- Soft start at power up
- Emergency stop button with LED indicator
- Low-battery shut down with LED indicator
- LED power and speed indication
- Speed regulation with motor feedback
- Minimum and maximum throttle range adjustment
- Maximum speed-limit setting
- PWM frequency adjustment from 100Hz to 1kHz (typical)

As you can see, the MOSFET is below the motor, on the 'low side'.

In the opposite case, the motor is connected to the negative terminal of the battery and the switching MOSFET is connected between the positive terminal of the battery and the positive terminal of the motor, and this 'high-side switching' arrangement is shown in Fig.1(b).

Arranging the gate drive signals to an N-channel MOSFET in a low-side switching circuit is comparatively simple since the source of the MOSFET is at 0V and this is easy with typical logic or microcontroller switching.

It is somewhat more complicated in a high-side switching circuit since the source terminal of the MOSFET is tied to that of the positive motor terminal and so when the motor has full voltage applied to it, the MOSFET's source voltage is almost equal to the battery voltage.

But when the motor has low or zero voltage applied to it, the MOSFET's source voltage is similarly low. This creates a problem with an N-channel MOSFET since it needs a gate voltage which is positive with respect to the source.

Consider then, a circuit with a nominal battery voltage of 48V and a MOSFET which requires a gate-source voltage of say, 10V to fully turn on. That would mean that the required gate voltage was about 58V, ie, 10V more than the battery voltage. How do you generate such high gate voltages which are tied to the source terminal and which need to 'float up and down' according to whether the MOSFET is turned on or off?

That task is performed by a 'high-side driver' IC, so we have one of those chips in our circuit, which we will now describe.

Circuit description

The full circuit of the *DC Motor Speed Controller* is shown in Fig.2. The section on the left-hand page describes the control PCB and it includes the PIC16F88 microcontroller (IC1), the International Rectifier IRS21850S high/low-side driver (IC2), two 3-terminal regulators and seven trimpots.

The section on the right-hand page describes the switching PCB and it

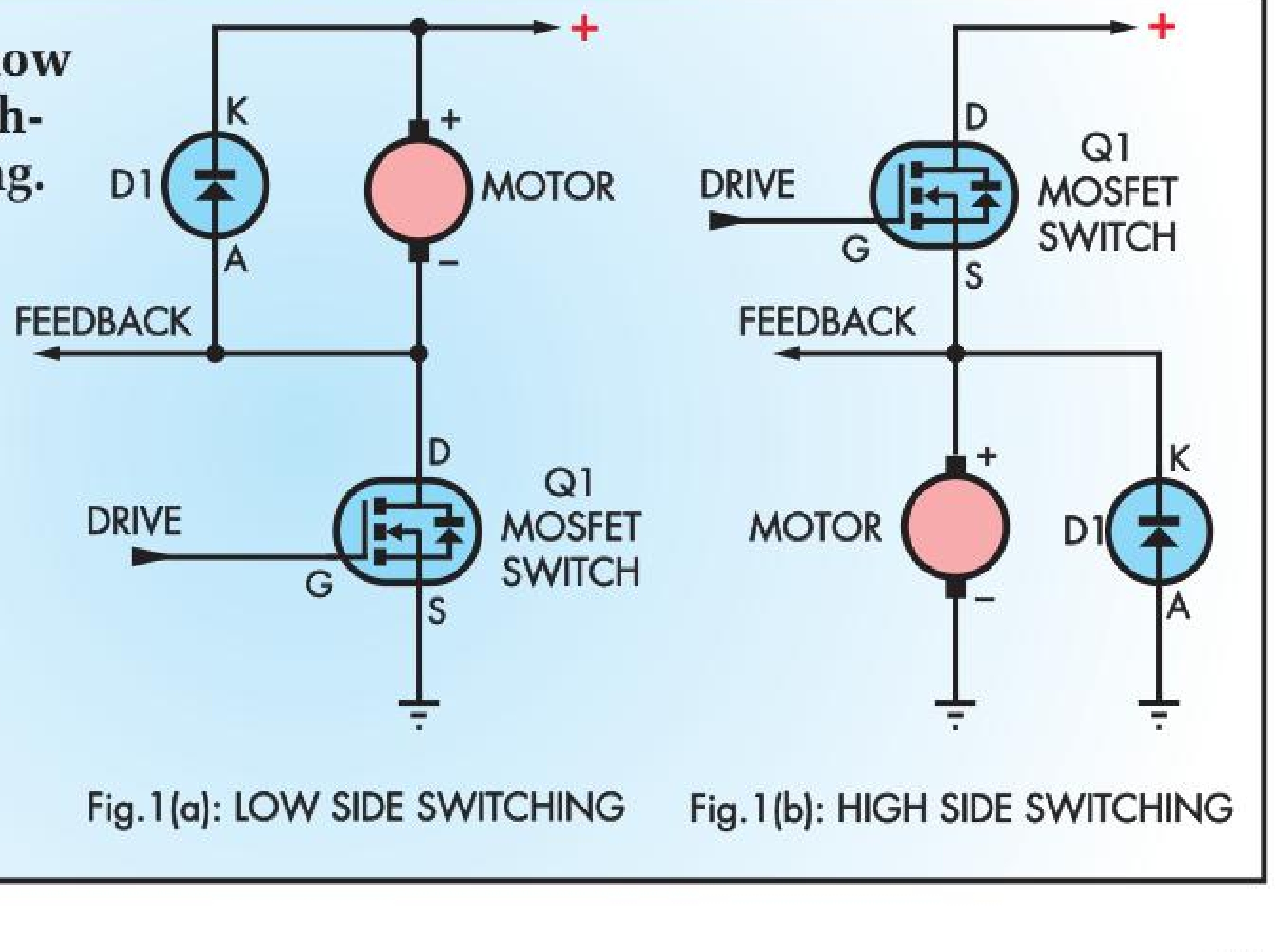


Fig.1(a): LOW SIDE SWITCHING

Fig.1(b): HIGH SIDE SWITCHING

Fig.1: these two circuits show the difference between high-side and low-side switching. This refers to the position of the control circuitry and motor with respect to the supply. In low side, the motor is switched, or controlled, between its negative connection and earth; in high side, between the motor positive and the positive supply.

includes the two (or three MOSFETs), the fast recovery diode (D1) and the all-important links which set the circuit up for high-side or low-side switching.

We will make this point up-front: it is absolutely crucial that you only install one set of links for high-side OR low-side switching.

If you (stupidly!) install *all* the links, you will create a short-circuit directly across the battery which will blow the fuse to smithereens as soon as the circuit is connected!

With that point out of the way, we will continue with the circuit description. Starting on the left-hand side of the circuit, the microcontroller monitors the speed input signal from a potentiometer (VR8) or a twist-grip Hall-effect throttle and produces a 5V pulse-width-modulated signal which is fed to IC2 where it is converted to a floating 0-12V signal suitable for the gates of either low or high-side-connected MOSFETs.

The speed signal from potentiometer VR8, ranging from 0 to 5V, is fed to the AN4 input of IC1 via a 2.2kΩ resistor. IC1's analogue-to-digital converter (ADC) converts the speed signal to digital form.

The ADC has two reference inputs, labelled REF− and REF+. These references provide the range over which the ADC measures and they are set using trimpots VR1 and VR2, respectively.

If a Hall-effect throttle is used, its output does not cover the full 0-5V range. So in this case, VR1 is used to set REF− to match the lowest voltage available from the Hall-effect throttle, and VR2 is used to set REF+ for the highest voltage from the sensor. The digital result from the ADC then covers the full 0-255 range.

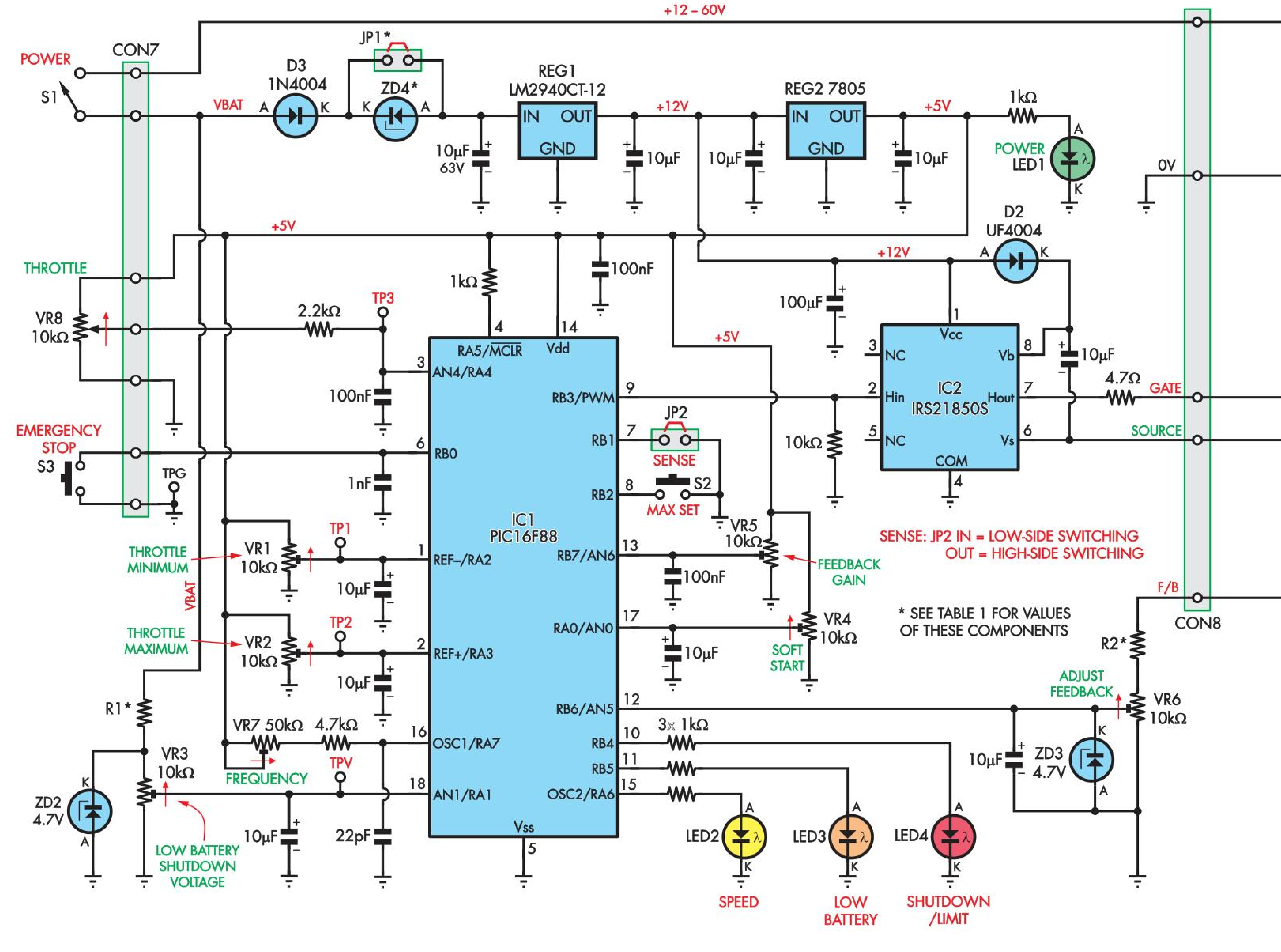
REF+ and REF− do have limit restrictions. REF+ can be set between 2.5V and 5V, while REF− can be from 0V up to 2V below REF+. So for a Hall-effect throttle that has a 0.75V minimum and 3.65V maximum, REF− is set for 0.75V, and REF+ set to 3.65V. These values are within the voltage limit restrictions.

So depending on the throttle setting, IC1's PWM output at pin 9 produces a 5V pulse stream with a duty cycle ranging from 0% (Off) to almost 100%. It does not go to the full 100% (ie, 5V), as will be explained later.

LED2, connected to pin 15 of IC1, flashes to mimic the duty cycle of the PWM signal; brief flashes at low-speed settings and longer flashes for higher-speed settings.

ADC references

While the throttle input at AN4 uses the REF+ and REF− settings from VR1 and VR2 as discussed above, the remainder of the analogue inputs to IC1 are converted using alternative references that are set up within the software.


+12 – 60V
POWER
CON7
S1
JP1*
D3
1N4004
ZD4*
VBAT
A
K
REG1
LM2940CT-12
IN
OUT
GND
10µF
63V
+12V
10µF
REG2 7805
+5V
1kΩ
POWER
LED1
0V
+5V
THROTTLE
VR8
10kΩ
2.2kΩ
TP3
1kΩ
100nF
D2
UF4004
+12V
100µF
EMERGENCY
STOP
S3
TPG
4
14
RA5/MCLR
Vdd
3
AN4/RA4
100nF
6
RB0
1nF
9
RB3/PWM
7
RB1
JP2
SENSE
8
RB2
S2
MAX SET
VR5
10kΩ
13
RB7/AN6
100nF
FEEDBACK
GAIN
17
RA0/AN0
10µF
VR4
10kΩ
SOFT
START
12
RB6/AN5
10
RB4
11
RB5
15
OSC2/RA6
3x 1kΩ
IC1
PIC16F88
1
REF−/RA2
2
REF+/RA3
16
OSC1/RA7
18
AN1/RA1
Vss
5
THROTTLE
MINIMUM
VR1
10kΩ
TP1
THROTTLE
MAXIMUM
VR2
10kΩ
TP2
VBAT
R1*
VR7 50kΩ
4.7kΩ
FREQUENCY
TPV
VR3
10kΩ
ZD2
4.7V
LOW BATTERY
SHUTDOWN
VOLTAGE
10µF
22pF
1
Vcc
3
NC
Vb
8
2
Hin
IC2
IRS21850S
Hout
7
5
NC
Vs
6
COM
4
10µF
4.7Ω
GATE
SOURCE
10kΩ
SENSE: JP2 IN = LOW-SIDE SWITCHING
OUT = HIGH-SIDE SWITCHING
* SEE TABLE 1 FOR VALUES
OF THESE COMPONENTS
F/B
CON8
R2*
ADJUST
FEEDBACK
VR6
10kΩ
10µF
ZD3
4.7V
LED2
LED3
LED4
SPEED
LOW
BATTERY
SHUTDOWN
/LIMIT

HIGH-POWER MOTOR SPEED CONTROLLER

Fig.2: the circuitry on this page is that on the 'control' PCB. IC1, a PIC16F88, monitors the settings of the various controls, along with monitoring the back-emf from the motor. It produces the PWM signal used to control the motor speed. . .

The first of these is for low-battery detection. The AN1 input, pin 18, monitors the battery voltage via resistor R1 and trimpot VR3. The input voltage to IC1 is limited by the 4.7V zener diode, ZD2. Table 1 shows the value of R1, depending on the nominal battery voltage.

The battery voltage is deemed to be low when the voltage at AN1 falls below 2.5V, assuming an exact 5V at pin 14 of IC1. If the voltage at AN1 drops below 2.5V, the MOSFETs are turned off and LED3 is lit up.

This condition will stay until the circuit is turned off and the battery voltage is increased (charge the battery?). Shutdown will re-occur if the battery voltage is still below the low-battery setting.

Speed regulation feedback

One of the tricky aspects of this circuit is providing for feedback of the motor back-EMF. As already noted, the back-EMF is proportional to the speed of the motor and it opposes the current. So when the motor is stalled (but voltage is applied) there will be no back-EMF and the current will be very high (this is the stall or locked-rotor current).

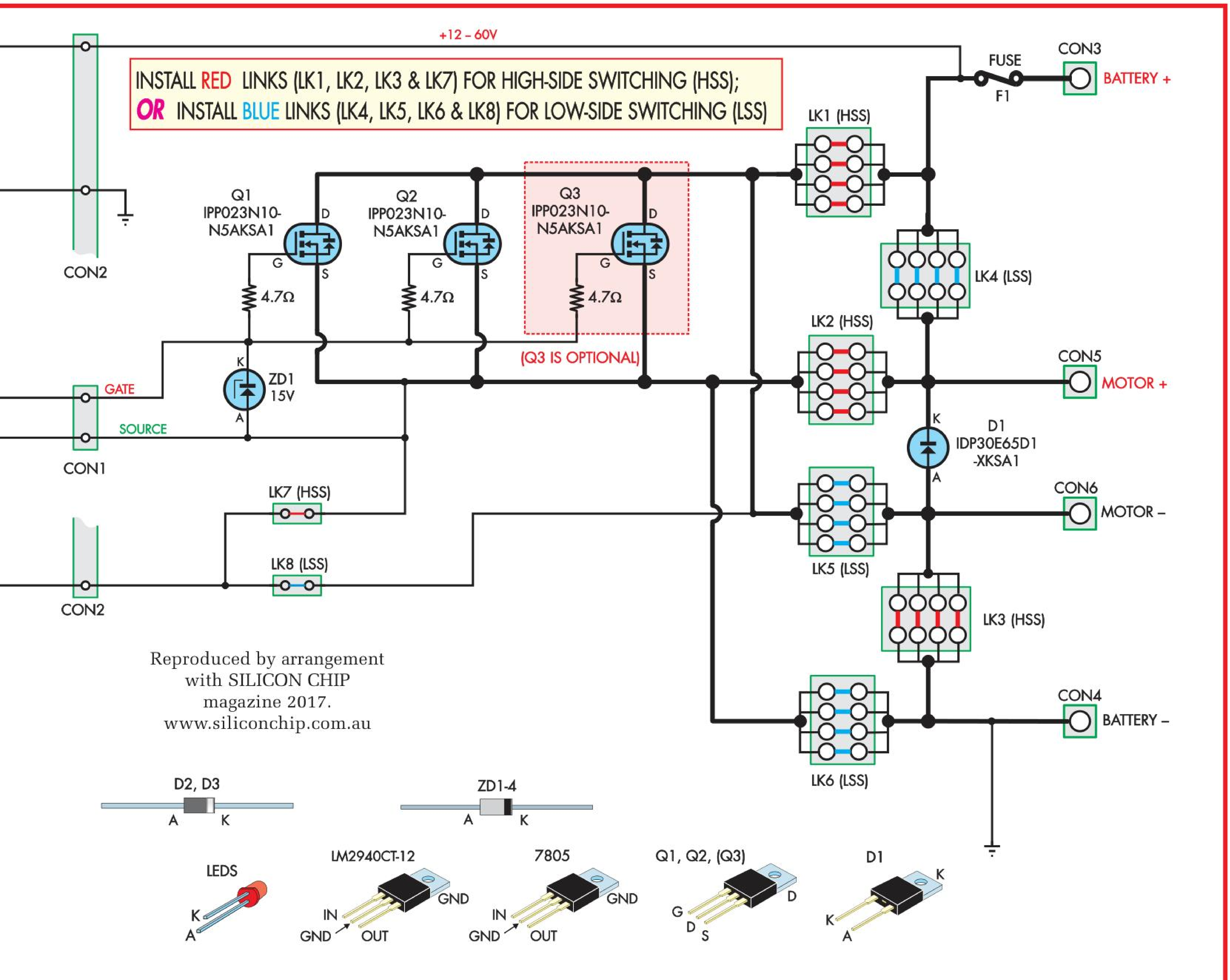
Conversely, when motor speed is high, the back-EMF will be high and the current will be correspondingly low. For example, with an applied voltage of 12V and the motor running at maximum speed, the back-EMF could be as high as 10V.

A further complication applies depending on whether the circuit is configured for high-side or low-side switching of the MOSFETs. In the high-side switching case (see Fig.1(b)), the back-EMF will vary from 0V to, say, 10V, with the DC supply being 12V.

That can be quite simply coupled back to the microcontroller. But in the low-side switching case, since one side of the motor is tied to the +12V rail, the back-EMF will vary from 12V (zero speed), to 2V (full speed). In other words, the back-EMF will be tied to the positive rail and will have the opposite sense.

There are two ways to cope with this problem. One method is to build a level-shifting inverting op amp circuit; but op amps that can cope with a supply voltage and common-mode voltages running to 60V or more are expensive and hard to get. The way around this is to use a level-shifting circuit using discrete transistors.

In this case though, we just reduce the back-EMF voltage to no more than 5V and let the microcontroller figure it out. So, looking for a moment at the right-hand side of the circuit, we take the feedback (back-EMF signal) from the commoned source electrodes of the MOSFETs (positive side of the motor) via link LK7 for the high-side switching circuit and from the


+12 – 60V
INSTALL RED LINKS (LK1, LK2, LK3 & LK7) FOR HIGH-SIDE SWITCHING (HSS);
OR INSTALL BLUE LINKS (LK4, LK5, LK6 & LK8) FOR LOW-SIDE SWITCHING (LSS)
CON2
Q1
IPP023N10-
N5AKSA1
Q2
IPP023N10-
N5AKSA1
Q3
IPP023N10-
N5AKSA1
D
G
S
4.7Ω
4.7Ω
4.7Ω
(Q3 IS OPTIONAL)
K
ZD1
15V
A
GATE
SOURCE
CON1
LK7 (HSS)
LK8 (LSS)
CON2
FUSE
F1
CON3
BATTERY +
LK1 (HSS)
LK4 (LSS)
LK2 (HSS)
CON5
MOTOR +
K
D1
IDP30E65D1
-XKSA1
A
CON6
MOTOR –
LK5 (LSS)
LK3 (HSS)
CON4
BATTERY –
LK6 (LSS)
D2, D3
A
K
ZD1-4
A
K
LEDS
K
A
LM2940CT-12
GND
IN
GND
OUT
7805
GND
IN
GND
OUT
Q1, Q2, (Q3)
G
D
S
D
D1
K
K
A

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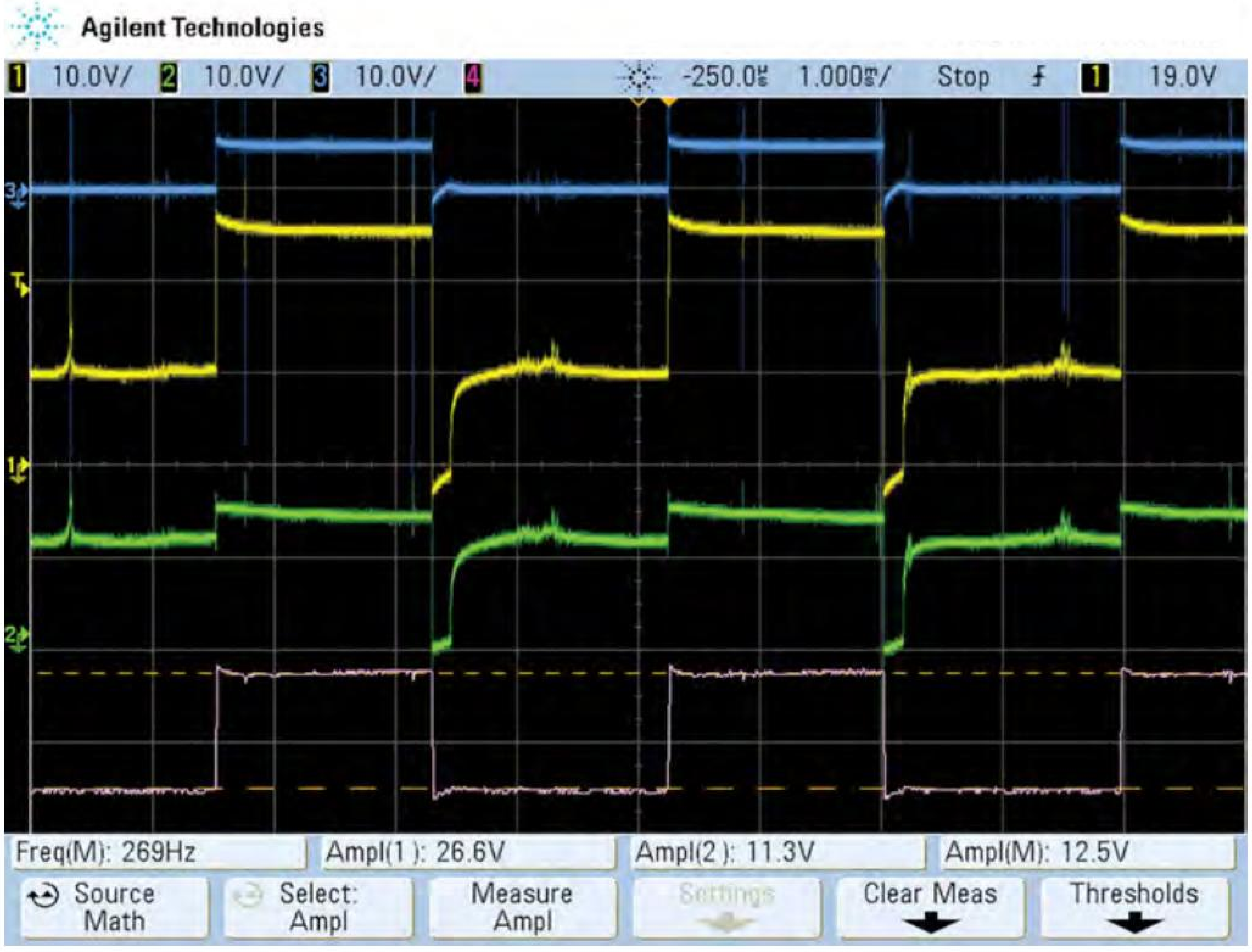
. . . while the circuitry on this page is all on the 'switching' PCB to actually drive the motor. As mentioned in the text, it is absolutely imperative that you ONLY install the red OR the blue links, depending on high or low-side switching.



Freq(M): 269Hz | Ampl(1): 26.6V | Ampl(2): 11.3V | Ampl(M): 12.5V

These waveforms show the operation of the *DC Motor speed controller*. The top (blue) trace is the PWM waveform from IC1. The yellow trace is the 'jacked up' gate wave-form from the high-side driver, IC2. The green trace is the voltage across the motor – note that it is smaller in amplitude than the gate waveform. Finally, the pink trace is the gate-source waveform (difference between traces 1 and 2).

Nominal supply voltage	R1 and R2	JP1	ZD4
12V	10kΩ	Jumper inserted	No zener
24V	27kΩ	No jumper	10V 1W
36V	47kΩ	No jumper	20V 1W
48V	68kΩ	No jumper	30V 3W

Table 1: resistor, zener and jumper settings for various battery voltages.

commoned drain electrodes of the MOSFETs via link LK8.

The feedback signal is fed via resistor R2 to the 'Adjust Feedback' 10kΩ trimpot VR6. The voltage from the wiper of VR6 is limited by 4.7V zener diode ZD3 and filtered to remove motor hash by the 10μF capacitor and then fed to pin 12 of the microcontroller, IC1.

The value of R2 is varied according to the supply voltage, as shown in Table 1 (above right).

We need to tell the microcontroller whether the circuit is high-side or low-side switching, and that is done with SENSE jumper link JP2, connected to the RB1 input at pin 7.

Normally, the sense input is held high (5V) via an internal pullup current and in that condition, the software works for a high-side driver. If the sense input is tied to 0V with link JP2, then the software works for low-side switching.

Speed limiting and PWM frequency

You can set the maximum motor speed in the following way. Press the speed limit switch S2 (connected to the RB2 input, pin 8) and set the throttle to the desired maximum speed and then release the switch. Once the maximum speed is set in this way, you can apply more throttle, but the duty cycle of the MOSFET switching will not increase beyond the limit.

IC1's PWM output switching frequency at pin 9 is set by 50kΩ trimpot VR7, the 4.7kΩ series resistor and the 22pF capacitor connected to pin 16, the RC oscillator clock input. VR7 allows you to set the PWM frequency over the range from 100Hz to 1kHz, as previously noted.

MOSFET switching

The PWM output signal from IC1 is fed to IC2 and it can drive the N-channel MOSFETs in high-side or low-side switching without any circuit changes being required.

Fig.3 shows a portion of the circuit of Fig.2. The PWM signal from IC1 is fed to pin 2 and IC2's pin 7 drives the gate (or gates) of the MOSFETs. IC2 has an internal floating supply that can raise its output up to 600V higher than the 12V supply rail, Vcc, applied between pins 4 and 1.

The internal floating supply is between Vb and Vs, and is essentially a 'bootstrapped' diode pump circuit. It depends on the MOSFET and load (in this case the motor) being connected. The MOSFET source connects to Vs (pin 6) and the gate connects to pin 7. With the MOSFET initially off, diode D2 charges the 10μF capacitor that's between pin 8 (Vb) and pin 6 (Vs) via the motor windings. At this point, the floating supply is sitting at about 12V and can provide a 12V gate signal to the MOSFET.

When the MOSFET gate is taken to 12V, it switches on and its source is pulled up to the positive battery supply. The source voltage pulls the negative side of the 10μF floating supply to the battery voltage (which can be up to 60V in our circuit) and the positive side of the 10μF capacitor is then 12V above the battery supply. Diode D2 is then reverse-biased.

When the gate signal drops to zero, the MOSFET switches off and

Inside the *DC Motor Speed Controller* – full construction details will be presented next month but will be slightly different from this prototype. The links on the motor PCB have been set up for high-side operation.

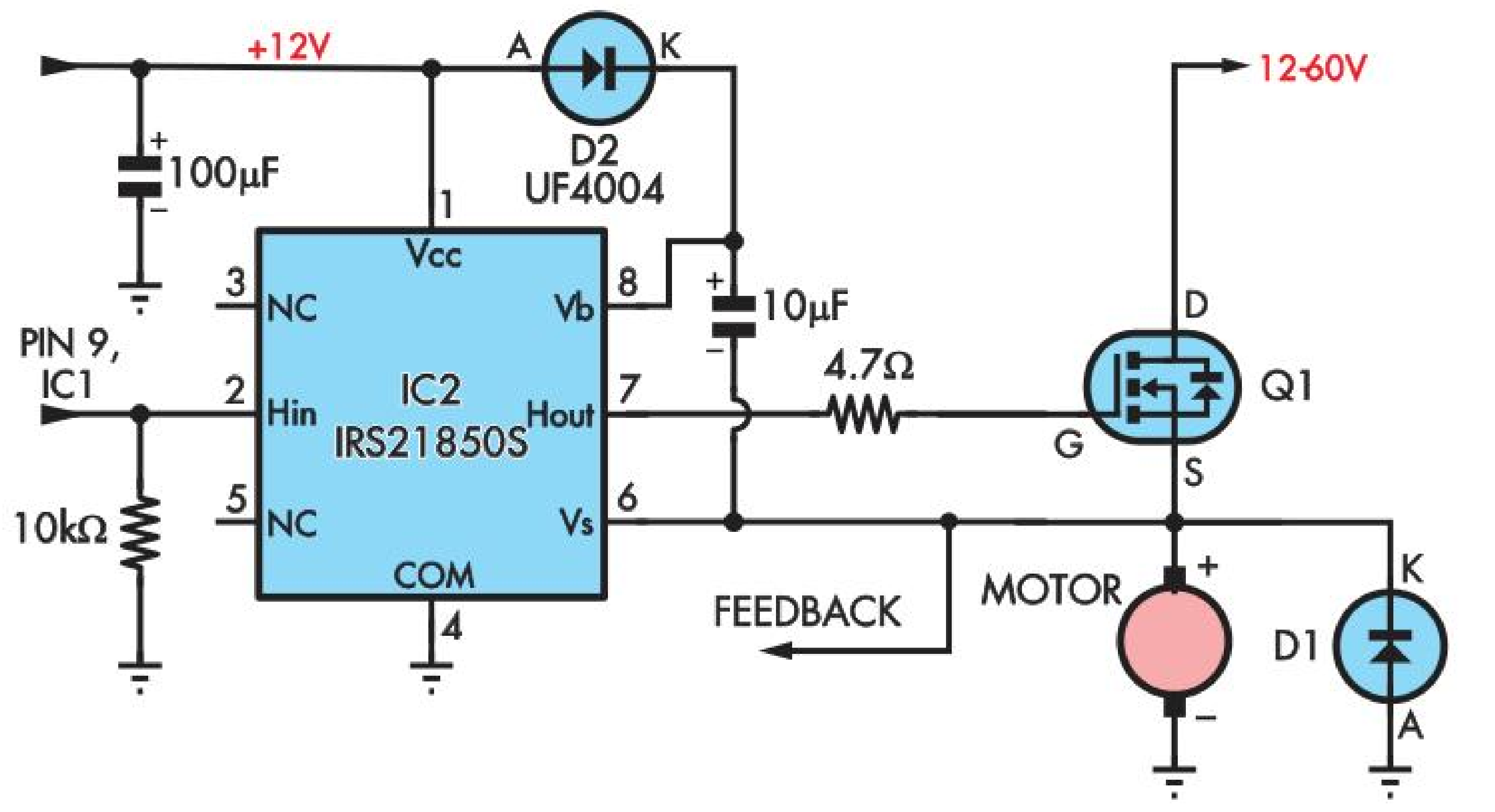


Fig.3: the high-side driver (IC2) generates its floating supply across the 10μF capacitor in a bootstrap mode, enabled by the switching of MOSFET Q1.

the 10μF capacitor is recharged 12V. In this way, IC2 can always deliver an adequate gate pulse voltage to turn on the MOSFET and drive the load.

However, for this process to work, the gate pulses can never have a duty cycle of 100%, ie, permanently high, because that would stop the diode pump involving D2 from working. In practice, the PWM duty cycle can reach 99% without the floating supply discharging. This is why the PWM duty cycle can never reach 100%, as noted earlier in this article.

In the low-side switching configuration, the floating supply in IC2 remains at ground level, due to Vs being connected to ground. IC2 is then used as a high-current MOSFET gate driver that translates the 0-5V from the PWM output of IC1 to 0-12V.

High-side and low-side switching configurations

It may not be obvious, but the change from low-side switching as shown in Fig.1(a), to high-side switching in Fig.1(b), is done by two sets of links and as already noted, **only one set of these links must be installed on the PCB**.

So for the high-side switching, you would install the parallel links LK1, LK2 and and LK3, as well as the feedback link LK7.

Similarly, for low-side switching, you must install paralleled links LK4, LK5 and LK6, together with feedback link LK8. These linking options essentially swap the positions of the MOSFETs and motor, to agree with Fig.1(a) or Fig.1(b).

Next month, we will complete the *DC Motor Speed Controller* with the construction details and explain its set-up procedure.

Parts List – DC Motor Speed Controller

Controller board

1 PCB available from the *EPE PCB Service*, coded 11112161, 107 × 82mm
1 set of panel labels
1 diecast box 119 × 94 × 57mm
2 3-way screw terminals with 5.08mm spacings (as part of CON7 and CON8)
3 2-way screw terminals with 5.08mm spacings (as part of CON7 and CON8)
1 SPST toggle switch (S1)
1 emergency shut-down switch latching DPDT pushbutton; S3; optional
1 momentary PCB-mount switch
1 DIL18 IC socket
2 2-way pin headers with 2.54mm spacings (JP1,JP2)
2 jumper shunts
1 knob to suit speed potentiometer
4 rubber feet
4 M3 tapped × 6.3mm spacers
10 M3 × 6mm screws
2 M3 nuts
1 cable gland for 4-8mm cable
1 500mm length of medium-duty hookup wire (or 5 100mm lengths of medium-duty hookup wire of different colours)
8 100mm cable ties
5 PC stakes (optional)

Semiconductors

1 PIC16F88-I/P microcontroller programmed with 1111216A.hex (IC1)
1 IRS21850SPBF high-side driver (IC2)
1 LM2940CT-12 low-dropout regulator (REG1)
1 7805 three-terminal regulator (REG2)
4 5mm LEDs (LED1 [green], LED2 [yellow], LED3 [amber], LED4 [red])
1 UF4004 1A fast diode (D2)
1 1N4004 1A diode (D3)
1 zener diode (ZD4) (see table 1)
2 4.7V 1W zener diodes (ZD2,ZD3)

Capacitors

1 10μF 63V PC electrolytic
9 10μF 16V PC electrolytic
1 100μF 16V PC electrolytic
3 100nF 63V or 100V MKT polyester
1 1nf MKT polyester
1 22pF ceramic

Resistors (0.25W, 1%)

1 10kΩ 1 4.7kΩ 1 2.2kΩ 5 1kΩ 1 4.7Ω
R1,R2: see Table.1
6 10kΩ miniature horizontal trimpots (code 103) (VR1-VR6)
1 50kΩ miniature horizontal trimpot (code 503) (VR7)
1 10kΩ linear potentiometer (VR8)

Power board

1 PCB available from the *EPE PCB Service,* coded 11112162, 111 × 85mm (70μm copper)
2 50A red jumbo binding posts (CON3,CON5)
2 50A black jumbo binding posts (CON4,CON6)
1 40A PCB mount standard ATO/ATC blade fuse holder (F1)
1 40A* ATO/ATC blade fuse (*rating to suit motor)
1 3-way screw terminals with 5.08mm spacings (CON2)
1 2-way screw terminals with 5.08mm spacings (CON1)
1 200mm length of 0.7mm tinned copper wire
1 600mm length of medium-duty hookup wire (or 6 100mm lengths of medium-duty hookup wire of different colours)
2 M3 tapped spacers, 12mm long
5 M3 × 10mm screws
2 IPP023N10N5AKSA1 120A 100V N-channel MOSFETs (Q1,Q2)
1 IDP30E65D1XKSA1 60A 650V diode (D1)
1 15V 1W zener diode (ZD1)
2 4.7Ω 0.25W resistors

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RX
Orangepip
Kona328
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ICSP
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RX
RESET EN
POWER
RESET
3.3V
5V
GND
GND
Vin
ANALOG
A0
A1
A2
A3
47
25v
VT

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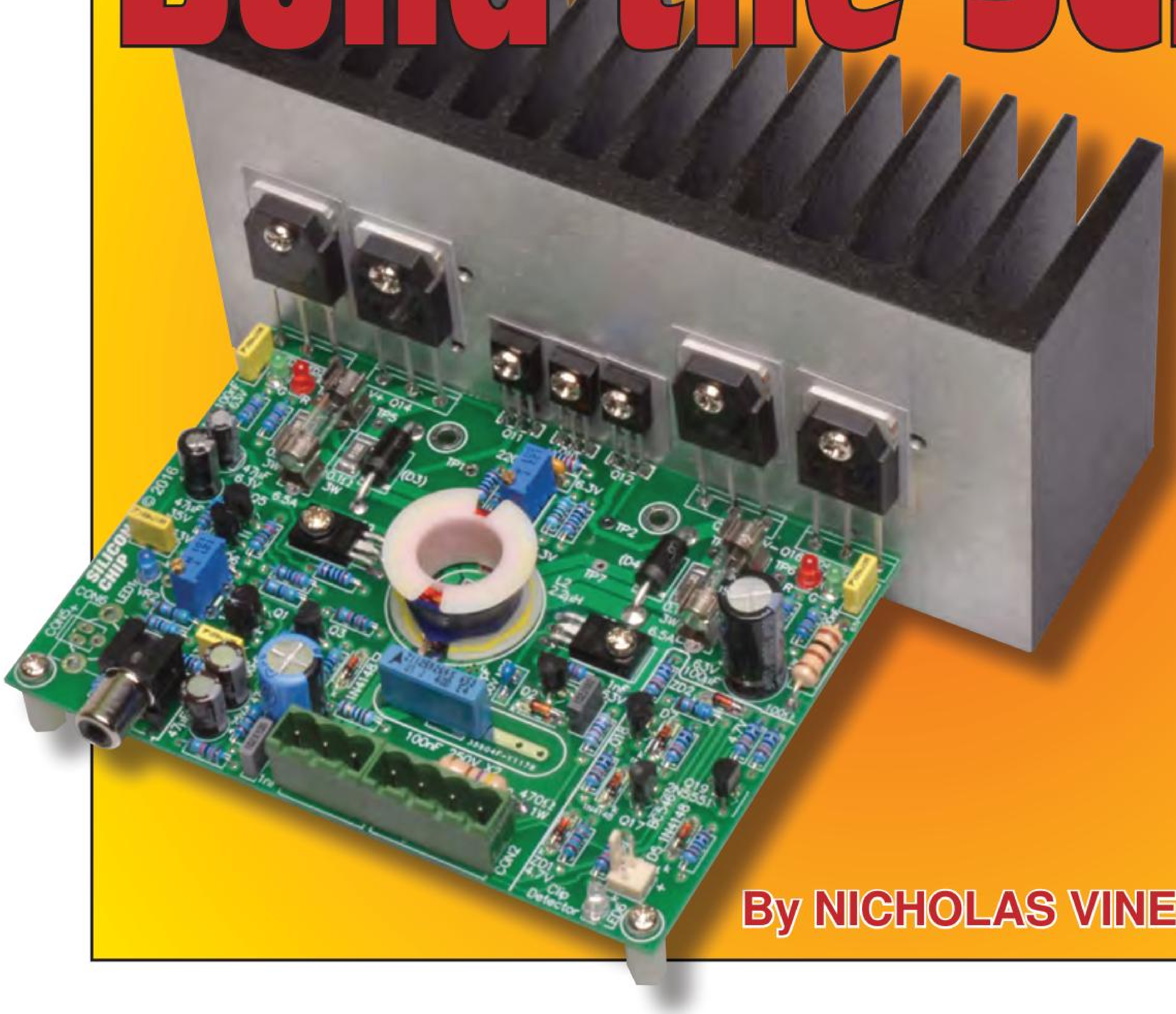
Part 1



This completely new amplifier circuit incorporates most of the features of modern amplifier modules, but uses easy-to-solder through-hole components. There are no tiny surface-mount components.

By NICHOLAS VINEN and LEO SIMPSON

Over the last 15 years or so, we have published a number of very popular audio amplifier modules. Some of these are best described as 'work-horse' designs, while others have been very low distortion, but being Class-A, they have the normal drawback of being quite inefficient.

So why are we producing this new *SC200 Module*? First, while earlier designs have been very successful, their distortion and noise performance could be improved. So in short,they are well overdue for a major upgrade.

Second, while some designs have been excellent, many used surface-mount components and would have been far easier to build – and presumably more popular – if through-hole components had been specified.

Main features

- ***Easy to build***
- ***Uses low-cost parts***
- ***Low distortion and noise***
- ***Compact PCB***
- ***Able to produce specified power output on a continuous basis with passive cooling***
- ***Onboard DC fuses***
- ***Power indicator LEDs***
- ***Fuse OK/blown indicator LEDs***
- ***Clipping indicator LED***
- ***Clean overload recovery with low ringing***
- ***Clean square-wave response with low ringing***
- ***Tolerant of hum and EMI fields***
- ***Survives brief short circuits/overload without blowing fuses***
- ***Quiescent current adjustment with temperature compensation***
- ***Output offset voltage adjustment***
- ***Output protection diodes (for driving 100V line transformers and electrostatic speakers)***

So in designing the *SC200 Module*, we have tried to make it much easier to build and at the same time, produce a module which is far ahead of ealier designs in all aspects of performance. All the semiconductors on the PCB are conventional through-hole components. Also, the small-signal transistors are readily available types and while the input pair of transistors won't give quite the same extremely low noise performance of some previous designs, they are cheap and readily available.

'Exotic' (ie, hard to source and/or expensive) devices have been avoided and this new design uses conventional 3-lead power transistors from Fairchild, types FJA4313 and FJA4213.

Main features

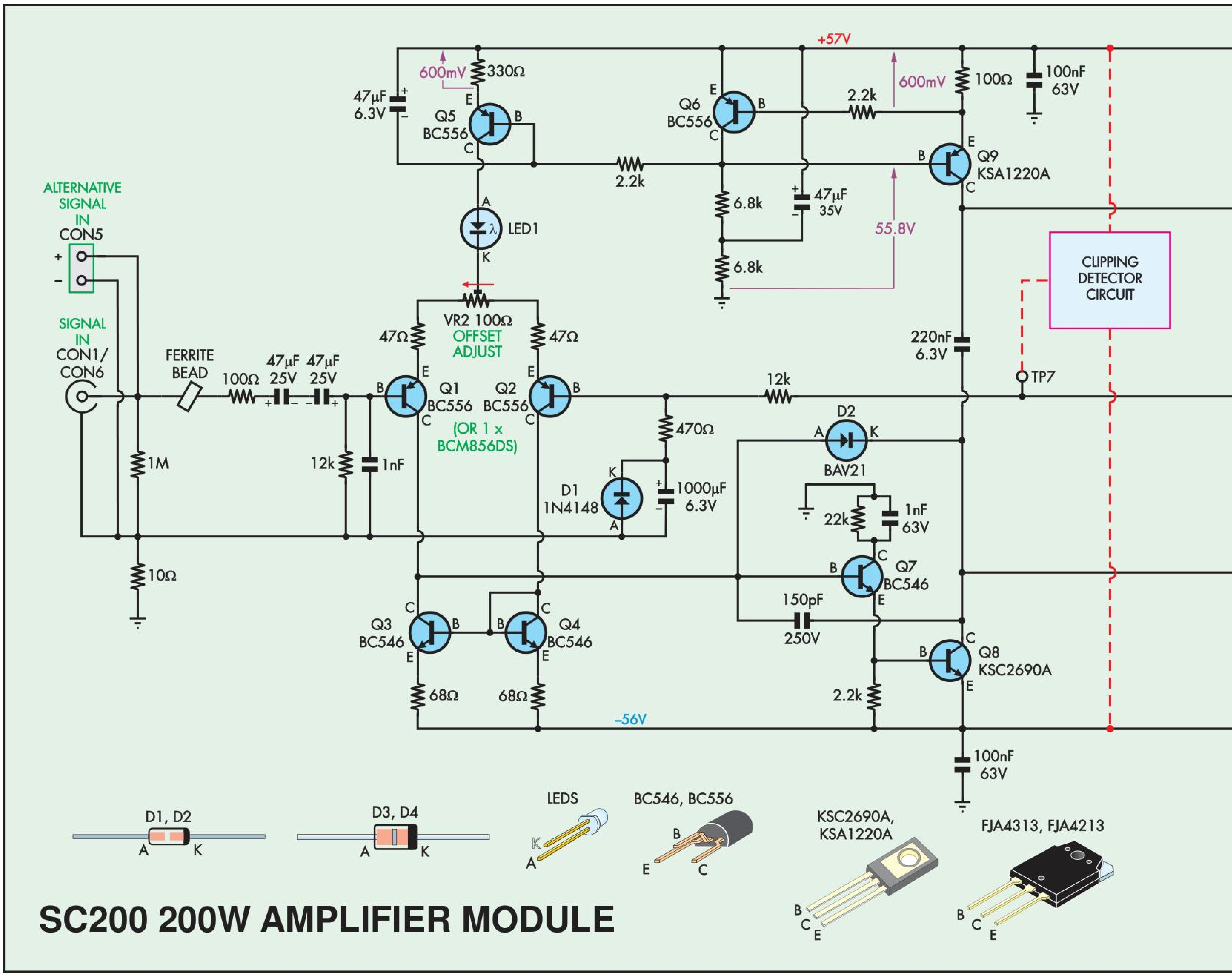
We've called this amplifier the 'SC200', indicative of its 200W power output into a 4Ω load. The design's main features are listed in a separate panel but some require additional comment.

Apart from exceptional performance, the *SC200* has quite a few features which were not thought of when we produced earlier amplifiers. These include on-board LEDs which indicate if the power rails are present and which change colour if the DC fuses blow.

And there is the clipping indicator circuit which drives an LED to show when the amplifier is being over-driven. This LED can be mounted on the amplifier front panel if desired and can be wired to multiple modules to indicate when any channel is clipping. Or you can simply have a clipping indicator for each channel in a stereo or surround sound amplifier.

Circuit description

The main amplifier circuit is shown in Fig.1. A 1MΩ resistor DC biases the input signal at RCA socket CON1 to 0V. The signal ground (ie, RCA socket shield) is connected


+57V
600mV
330Ω
47µF
6.3V
Q5
BC556
E
B
C
Q6
BC556
2.2k
600mV
100Ω
100nF
63V
Q9
KSA1220A
2.2k
6.8k
47µF
35V
55.8V
6.8k
ALTERNATIVE SIGNAL IN
CON5
+
–
LED1
A
K
VR2 100Ω
OFFSET ADJUST
47Ω
47Ω
CLIPPING DETECTOR CIRCUIT
220nF
6.3V
TP7
SIGNAL IN
CON1/
CON6
FERRITE BEAD
100Ω
47µF 25V
47µF 25V
Q1
BC556
Q2
BC556
(OR 1 x BCM856DS)
12k
D2
BAV21
470Ω
1000µF
6.3V
D1
1N4148
1M
12k
1nF
22k
1nF
63V
Q7
BC546
10Ω
150pF
250V
Q3
BC546
Q4
BC546
Q8
KSC2690A
68Ω
68Ω
2.2k
–56V
100nF
63V
D1, D2
D3, D4
LEDS
BC546, BC556
KSC2690A, KSA1220A
FJA4313, FJA4213
B
C
E

SC200 200W AMPLIFIER MODULE

to power ground via a 10Ω resistor, which improves stereo separation when modules share a power supply; it prevents a ground loop due to the grounds being joined directly both at the power supply module and at the signal source.

The signal passes through an RF-attenuating RC low-pass filter (100Ω/1nF plus ferrite bead) and is coupled to the base of PNP transistor Q1 via a pair of series-connected 47µF 25V electrolytic capacitors (which are together more compact and cost less than an equivalent non-polarised capacitor).

A 12kΩ resistor provides a path for Q1's base current to flow to ground. We have used readily available BC556 low-noise PNP input transistors for the input differential pair, Q1 and Q2. The input signal goes to the base of Q1, while negative feedback from the output goes to the base of Q2.

Both transistors have 47Ω emitter degeneration resistors for improved linearity, and they are fed with a common 2mA current via trimpot VR2 and power indicator LED1.

VR2 allows the current split to be shifted slightly between the two transistors to trim out base-emitter voltage mismatch and thus practically eliminate any output offset, and avoid excessive DC current when driving a line transformer or electrostatic speaker. LED1 has no effect on the operation of the circuit except to indicate when it is powered.

The currents from Q1 and Q2 go to a current mirror comprising two BC546 NPN transistors Q3 and Q4. The 68Ω emitter resistors help ensure that equal current flows through each transistor as the voltage across these resistors is much greater than the base-emitter voltage difference between the two.

Since the currents through Q3 and Q4 are held equal, any difference between the current from Q1 and Q2 must flow to the base of NPN transistor Q7. Thus, Q7's base current is proportional to the difference in input and feedback voltages. It forms the first half of a compound (Darlington-like) pair along with Q8, a 160V high-gain transistor. A 2.2kΩ resistor between its base and emitter speeds up switch-off.

Q7 and Q8 together form the Voltage Amplification Stage (VAS). Q8 has a constant-current source for its collector load, comprising Q6 and Q9. Together, these set the collector current for Q8 at around 6.5mA. As a result, the current flow to the base of Q7 is translated linearly to a voltage at Q8's collector, which controls the output stage.

PNP transistor Q5 provides a constant current of around 2mA to the input pair, and both it and Q9 are driven by Q6, which is set up to maintain a constant voltage across their emitter resistors. In other words, Q6 biases the bases of Q5 and Q9 to maintain an essentially static current through their collector-emitter junctions.

Output stage

The output stage consists of two pairs of Fairchild power transistors arranged as complementary emitter-followers. NPN transistors Q13 and Q14 are connected in parallel and source current for the speaker, while Q15 and Q16 are PNP types and sink current from the speaker.

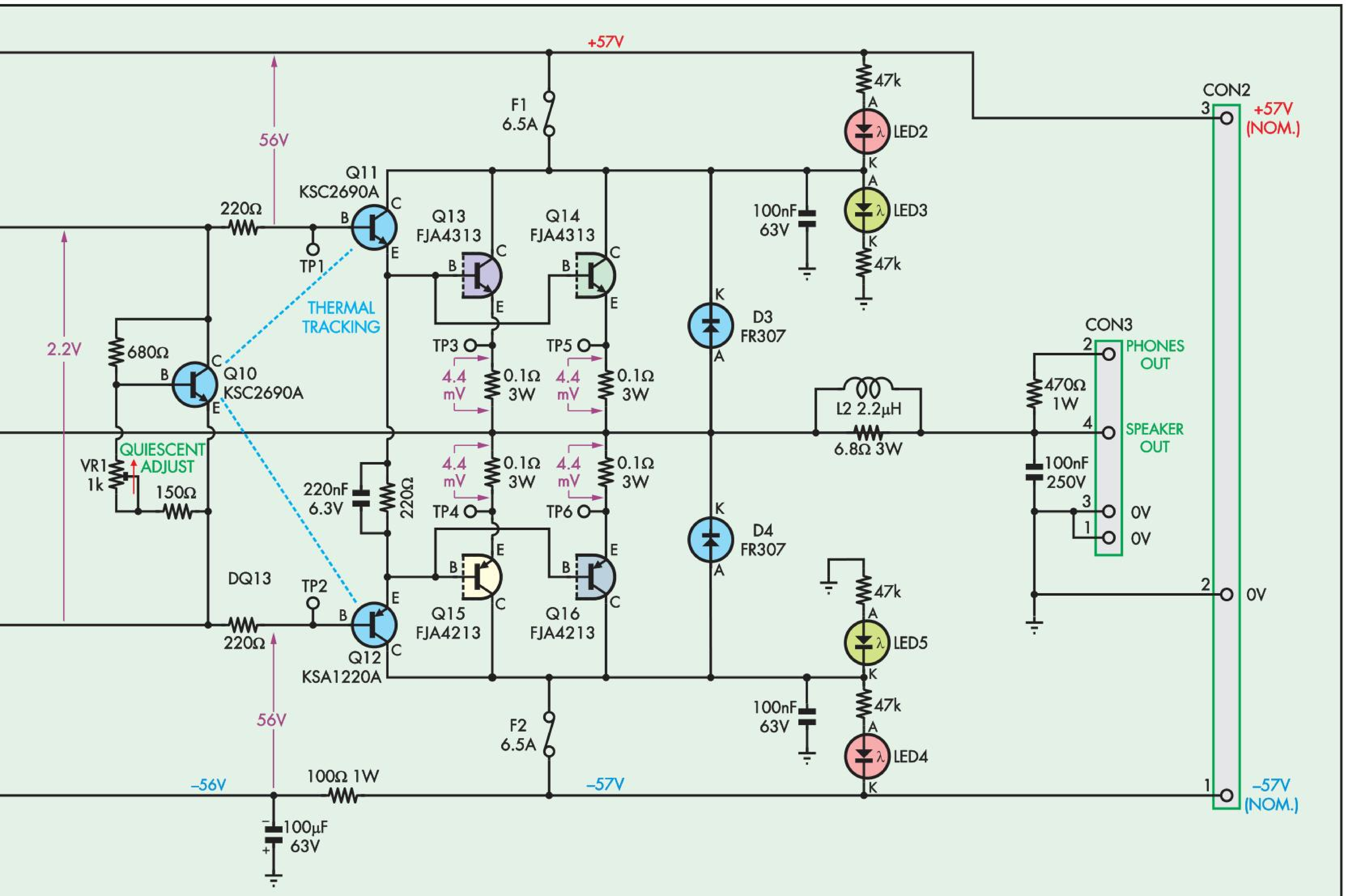


Fig.1: the complete circuit for the ***SC200 Amplfier Module*** **minus the circuitry for the clipping detector, which is shown separately in Fig.2. Q1 and Q2 are the input transistors, while Q5 and Q6 are the constant-current source. The signal from the collector of Q1 is fed to the base of Q7, which together with Q8 forms the voltage amplification stage. Q9 is the constant current load for Q8, providing very linear operation. Q10 is the V_{BE} multiplier and provides a floating voltage source which biases the complementary Darlington output stage.**

Surface-mount 3W 0.1Ω 1% emitter resistors ensure equal current sharing, linearise the output stage and produce a small amount of local feedback. They also serve as handy shunts for measuring the quiescent current.

Large power transistors require substantial base current due to limited gain; this is supplied by driver transistors Q11 and Q12. These effectively make the output stage a complementary Darlington.

The parallel 220Ω resistor and 220nF capacitor between the driver emitters speed up their switch-off when drive is being handed off from one to the other.

Quiescent current stabilisation

The four base-emitter junctions in the output stage, plus the voltage across the emitter resistors adds up to around 2.2V (as shown just to the left of Q10 in the circuit diagram) and thus a similar DC bias must be maintained between the bases of Q11 and Q12 to keep the output transistors in partial conduction most of the time; otherwise, there will be substantial crossover distortion each time the signal passes through 0V.

The reason is that when the signal polarity changes (ie, from positive to negative or vice versa), the output current drive is handed off from one set of output transistors to the other; ie, from Q13 and Q14 to Q15 and Q16, or the other way around.

This transition has to be smooth or else there will be a step in the output voltage and the way to smooth it is to ensure that there is overlap between the conduction of both pairs. In other words, with the output at zero volts, all four transistors are passing some current. This is known as the quiescent current.

This partial conduction requirement is a defining characteristic of Class-AB (otherwise, it would be Class-B).

To maintain a more-or-less constant quiescent current we need a 'floating' voltage source of 2.2V between the bases of Q11 and Q12, and this is provided by the V_{BE} multiplier Q10 and its associated components.

However, since the base-emitter voltages of the six transistors in the output stage all vary with temperature, a fixed floating voltage source is not suitable.

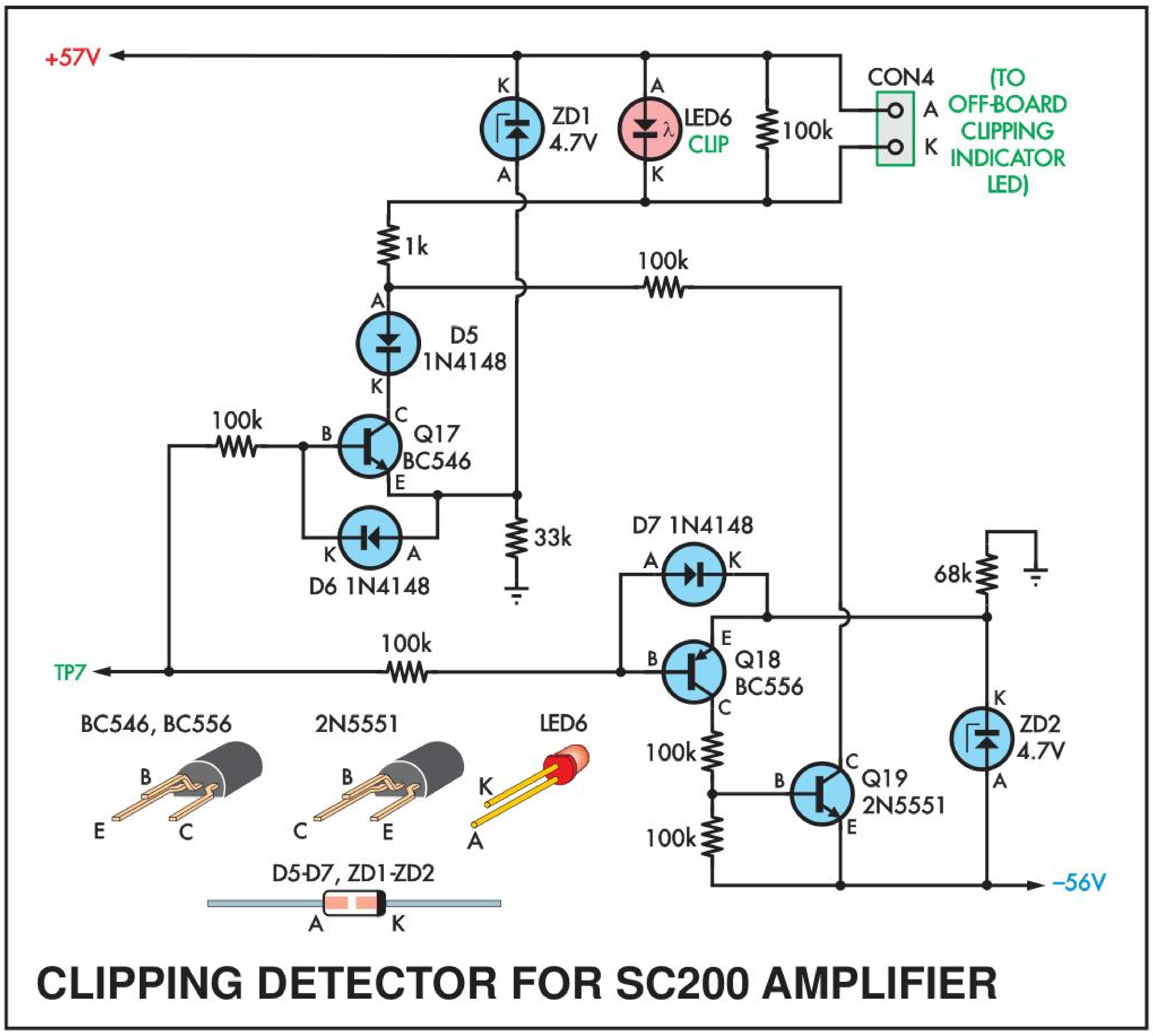
The base-emitter voltages drop with increasing temperature at around 2mV/°C, so a fixed voltage source of 2.2V would lead to increased current as the output transistors heated up and ultimately, to thermal runaway and destruction.

V_{BE} multiplier

So our floating voltage source must not only be adjustable, to compensate for manufacturing variations in the output transistors and emitter resistors, it must also automatically reduce the bias as the amplifier heats up, so that the quiescent current remains reasonably constant.

But first, let's explain the basic concept of a 'V_{BE} multiplier' before we consider how it tracks and adjusts for changes in operating temperature.

The V_{BE} multiplier is sometimes referred to as an 'amplified diode' and this gives some insight into its operation. Consider that the base-emitter voltage of a conducting transistor is around 0.6V. The bias network to our V_{BE} multiplier comprises the 680Ω



CLIPPING DETECTOR FOR SC200 AMPLIFIER

Fig.2: the clipping detector monitors the output waveform and lights LED6 whenever the output voltage comes within about 4V of either supply rail. This indicates the onset of clipping. NPN transistor Q17 detects positive signal excursions, while PNP transistor Q18 detects when the output signal approaches the negative rail.

resistor between collector and base and the 1kΩ trimpot and 150Ω resistor between base and emitter. This forms a divider between its collector and emitter, with a tap at the base.

We already know that the voltage between base and emitter is 0.6V and since the beta (DC current gain) of the transistor is quite high (>100), it will draw negligible base current, so the current through the two resistors and trimpot VR1 will essentially be identical. Furthermore, since we will have 0.6V between base and emitter, it follows that we need 1.6V between collector and base, if we are to obtain 2.2V between collector and emitter.

So, to adjust the resistance of VR1 to obtain 1.6V between collector and emitter, we need a resistance ratio between collector/base and base/emitter of 1.6V÷0.6V or 2.6666:1. This means the total resistance of VR1 and its series 150Ω resistor will be 680Ω × 0.6 ÷ 1.6 = 255Ω. And that means that trimpot VR1 must be set to a value of 255Ω – 150Ω = 105Ω.

We can therefore calculate the total resistance of the divider between collector and emitter at around 255Ω + 680Ω = 935Ω and therefore 2.2V / 935Ω = 2.35mA will flow through it.

The remainder of the 6.5mA (ie, 4.15mA) must flow through the collector/emitter junction of Q10.

But what if the external operating conditions around the V_{BE} multiplier act to increase the voltage between its collector and emitter above 2.2V? If that did happen, the resistive divider would cause its base-emitter voltage to increase but that would force the transistor to turn on harder and that would have the effect of reducing the collector-emitter voltage.

So the V_{BE} multiplier transistor is instead forced to operate with a constant collector-emitter voltage! In other words, it operates as a shunt voltage regulator, maintaining a constant voltage across the collector/emitter junction even if the current passing through it varies (but as long as it's higher than the 2.35mA required for the divider to operate properly).

Thermal tracking

So how does V_{BE} multiplier transistor Q10 adjust for temperature changes in the output transistors? We make it do that by mounting Q10 on the heatsink immediately between driver transistors Q11 and Q12. Furthermore, Q10 is the same transistor type as Q12, so the thermal tracking of the driver transistors and by extension, that of the four output power transistors, is quite good; not perfect, but quite good.

So if the temperature of the heatsink rises by 50°C, that would mean that the required base-emitter voltages of all seven transistors (for a given collector current) on the heatsink will reduce by 50 × 2mV = 100mV.

If the base-emitter voltage of Q10 has reduced by 100mV, given that it operates with a gain of (1.6 + 0.6)÷0.6 = ~3.7 times, the voltage of our floating source will be reduced to 2.2V – 100mV × 3.7 = 1.83V and this voltage will be applied across the four base-emitter junctions of the complementary Darlington output stage transistors. That means that even though the transistor junction temperatures may have increased by 50°C, their quiescent current should remain much as it was at much lower temperatures.

In practice, the process is not quite that good, so we also have local

Specifications

Output power (230VAC mains)	*200W RMS into 4Ω, 135W RMS into 8Ω*
Frequency response (10Hz-20kHz)	*+0,–0.05dB (8Ω); +0,–0.12dB (4Ω)*
Input sensitivity	*1.26V RMS for 135W into 8Ω; 1.08V RMS for 200W into 4Ω*
Input impedance	*11.85kΩ shunted with 1nF*
Rated Harmonic Distortion (4Ω, 8Ω)	*<0.01%, 20Hz-20kHz, 20Hz-30kHz bandwidth*
Signal-to-noise ratio	*–116dB unweighted with respect to 135W into 8Ω(20Hz-20kHz)*
Damping factor	*~250*
Stability	*unconditionally stable with any nominal speaker load ≥4Ω*
Music power	*170W (8Ω), 270W (4Ω)*
Dynamic headroom	*1dB (8Ω), 1.3dB (4Ω)*
Power supply	*±57V DC from a 45-0-45 transformer*
Quiescent current	*88mA nominal*
Quiescent power	*10W nominal*
Output offset	*typically <10mV untrimmed; <1mV trimmed*

feedback provided by the 0.1Ω 3W emitter resistors for the output transistors. If the voltage across these emitter resistors increases, due to increasing quiescent current, that will tend to reduce the base-emitter voltage (by subtraction) and therefore the current will reduce (or at least, not increase by as much as it would without them).

By the way, the 220Ω resistors between either end of the V_{BE} multiplier Q10 and Q11/Q12 act as RF stoppers and also limit current flow under fault conditions (eg, a short circuit).

Feedback and compensation

Negative feedback goes from the junction of the output emitter resistors to the base of Q2 via a 12kΩ/470Ω resistive divider, setting the closed-loop gain to 25.5 times (+28.5dB). The bottom end of the feedback network is connected to ground via a 1000µF electrolytic capacitor.

This has a negligible effect on the low-frequency response, but sets the DC gain to unity, so that the input offset is not magnified at the output by the gain factor of 25.5.

The 150pF compensation capacitor is connected between the collector of Q8 and the base of Q7, ie, it is effectively a Miller capacitor for the VAS 'Darlington' (in a real Darlington, the collectors would be common). This is a single-pole compensation arrangement which rolls off the open-loop gain at a high frequency to give unconditional stability with highly reactive loads across the amplifier's output.

The 22kΩ resistor in series with the collector of Q7 limits its current under fault conditions. Should the amplifier outputs be shorted, it will try to pull the output either up or down as hard as possible, depending on the offset voltage polarity.

If it tries to pull it up, the output current is inherently limited by the approximate 6.5mA current source driving Q11 from Q9. However, if it tries to pull down, Q8 is capable of sinking much more than 6.5mA.

The 22kΩ resistor limits Q8's base current to around 2mA and since Q8 has a beta of around 120, Q8's collector will not sink much more than 240mA. This is still enough to burn out Q12's 220Ω base resistor, but that may be the only damage from an extended short circuit; very brief short circuits should not cause any lasting damage.

Note that the 22kΩ resistor will cause Q7's collector voltage to drop as it is called on to supply more current, and the Early effect means its gain will drop when this happens. This can cause local negative feedback and oscillation. A low-value

Parts list – SC200 Amplifier Module

1 double-sided PCB available from the *EPE PCB Service*, coded 01108161, 117 × 84mm
1 diecast heatsink, 200 × 75 × 28mm
4 M205 fuse clips (F1,F2)
2 6.5A fast-blow M205 fuses (F1,F2)
1 small ferrite bead (FB1)
1 2.2µH air-cored inductor (L2) (***or*** 1 20mm OD × 10mm ID × 8mm bobbin and 1m of 1.25mm diameter enamelled copper wire, plus 10mm length of 20mm diameter heatshrink tubing)
1 1kΩ 25-turn vertical trimpot (VR1)
1 100Ω mini horizontal trimpot (VR2)
1 switched horizontal RCA socket (CON1) OR
1 2-pin polarised header (CON5) OR
1 vertical RCA socket (CON6)
1 4-way pluggable terminal block with socket, Dinkle 4EHDV or equivalent (CON2)
1 4-way pluggable terminal block with socket, Dinkle 3EHDV or equivalent (CON3)
4 TO-3P insulating washers
3 TO-126 or TO22- insulating washers
7 15mm M3 machine screws with nuts
6 6mm M3 machine screws with nuts
4 9mm M3 tapped nylon spacers
8 PCB pins (optional; TP1-TP7)

Semiconductors
2 FJA4313 250V 17A NPN transistors, TO-3P (Q13,Q14)
2 FJA4213 250V 17A PNP transistors, TO-3P (Q15,Q16)
3 KSC2690A medium-power NPN transistor (Q8,Q10,Q11)
2 KSA1220A medium-power PNP transistors (Q9,Q12)
3 BC546 NPN transistors (Q3,Q4,Q7)*
4 BC556 PNP transistors (Q1,Q2,Q5,Q6)*
1 blue 3mm or SMD 3216/1206 LED (LED1)
2 red 3mm or SMD 3216/1206 LEDs (LED2,LED4)
2 green 3mm or SMD 3216/1206 LEDs (LED3,LED5)
1 1N4148 small-signal diode (D1)*
1 BAV21 high-speed signal diode (D2)*
2 FR307 3A fast-recovery diodes (D3,D4)

Capacitors
1 1000µF 6.3V electrolytic
1 100µF 63V electrolytic
1 47µF 35V electrolytic
3 47µF 25V electrolytic
2 220nF 50V multi-layer ceramic or MKT
1 100nF 250VAC MKP
4 100nF 63V/100V MKT
2 1nF 63V/100V MKT
1 150pF 250V C0G/NP0 ceramic or MKT/MKP

Resistors (all 0.25W, 1% unless otherwise specified)
1 1MΩ 4 47kΩ 1 22kΩ
2 12kΩ 2 6.8kΩ 3 2.2kΩ
1 680Ω
1 470Ω 1W 5% through-hole or SMD 6332/2512
1 470Ω 1 330Ω 3 220Ω
1 120Ω
1 100Ω 1W 5% through-hole or SMD 6332/2512
2 100Ω 2 68Ω 2 47Ω
1 10Ω
1 6.8Ω 1% 3W SMD 6332/2512
4 0.1Ω 1% 3W SMD 6332/2512

Additional parts for clipping detector circuit

1 2-pin header and matching plug (optional; CON4)

Semiconductors
1 BC546 NPN transistor (Q17)*
1 BC556 PNP transistor (Q18)*
1 2N5551 high-voltage NPN transistor (Q19)
1 yellow, amber or red LED (LED6)
2 4.7V 0.4W/1W zener diodes (ZD1,ZD2)*
3 1N4148 small-signal diode (D5-D7)*

Resistors (all 0.25%, 1%)
6 100kΩ 1 68kΩ 1 33kΩ 1 1kΩ

**** SMD versions can be substituted; see text next month***

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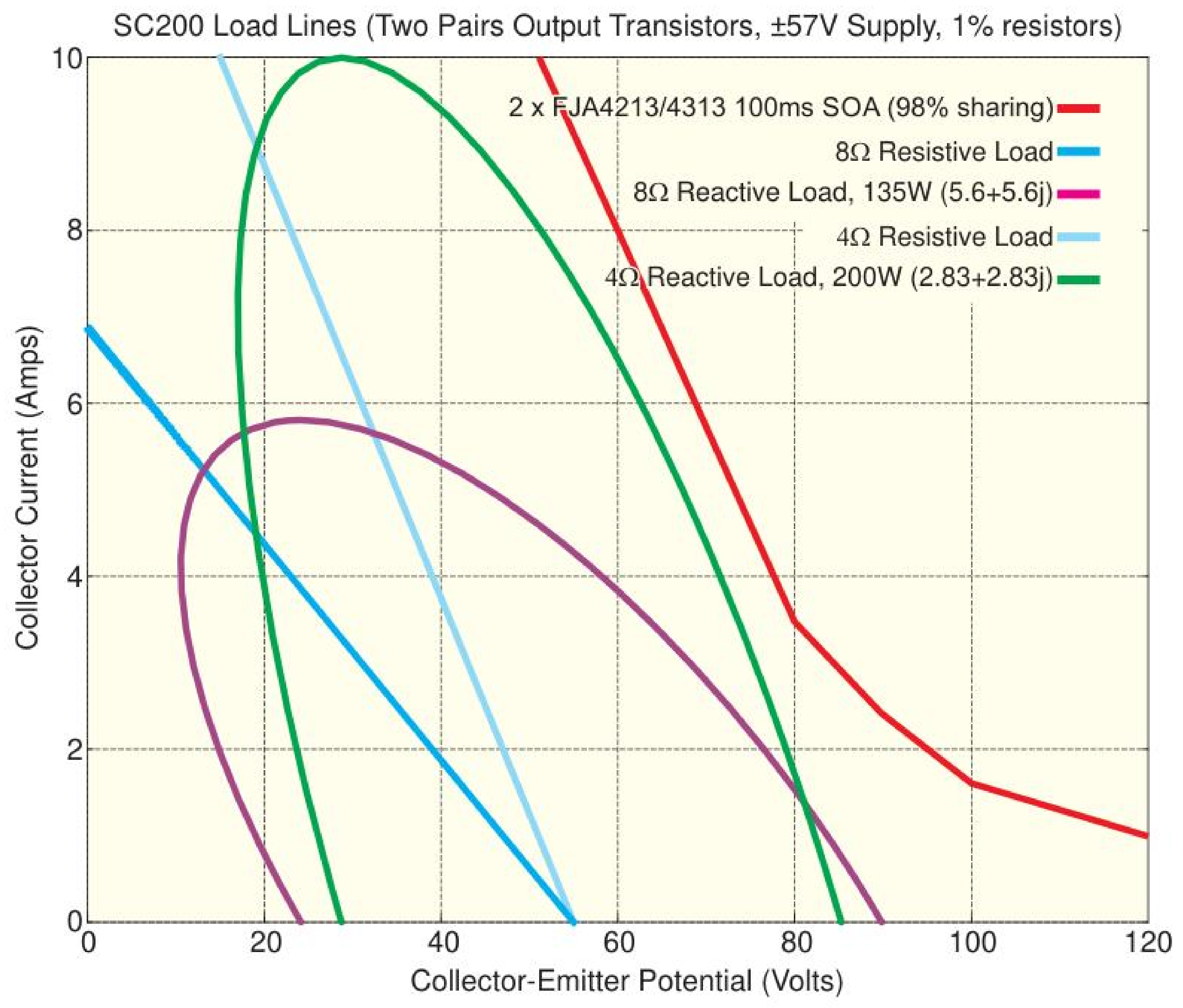

Fig.3: this diagram shows resistive (straight) and reactive (curved) load lines for operation into loudspeaker loads. Note that all the load lines are comfortably inside the safe operating area (SOA – red line) of the paralleled output transistors.

capacitor in parallel with the 22kΩ resistor prevents this while still allowing the current to Q8's base to quickly drop to 2mA during a short circuit.

Output filter

The 0.1Ω 3W emitter resistors of output transistors Q13-Q16 are connected to the output at CON3 via an RLC filter comprising a 2.2µH series inductor in parallel with a 6.8Ω 3W surface-mount resistor, with a 100nF capacitor across the output terminals. The inductor isolates any added capacitance at the output (eg, from the cables or the speaker's crossover network) from the amplifier at high frequencies, which could otherwise cause oscillation. The resistor reduces the inductor's Q to damp ringing, and also forms a Zobel network in combination with the 100nF capacitor, which also aids stability.

Driving a line transformer

While a very low output offset voltage gives slight benefits when driving normal speakers, it's absolutely critical when driving a 100V line transformer (for professional PA applications) or electrostatic speaker (which will typically have an internal transformer).

That's because the DC resistance of the primary winding will be much lower than that of a loudspeaker's voice coil, so a lot of DC current can flow with an output offset voltage of just a few millivolts.

WARNING!

High DC voltages (ie, ±57V) are present on this amplifier module. In particular, note that there is 114V DC between the two supply rails. Do not touch any wiring (including the fuseholders) when the amplifier is operating, otherwise you could get a lethal shock.

The other requirement for driving a transformer is to have protection diodes on the amplifier output to clamp inductive voltage spikes which occur when the amplifier is driven into clipping (overload).

These would otherwise reverse-bias the output transistor collector-emitter junctions, possibly causing damage. D3 and D4 are 3A relatively fast recovery diodes with low junction capacitance for their size and we have checked that they do not have any impact on performance.

So there should be no changes necessary to use this module in a PA amplifier or to drive electrostatic speakers, as long as the output offset voltage is trimmed out during set-up.

Indicator LEDs

We have already mentioned a blue LED1 connected in series with the input pair current source and which is lit whenever the board has power applied. Since there is an ~50V drop required from Q5's collector to VR2's wiper, the power to operate this LED is effectively free.

We've also included red/green LEDs LED2-LED5 to indicate the status of the output stage power rails. It isn't always obvious that a fuse has blown without careful inspection.

In the case of LED2, assuming F1 has not blown, the voltage at either end of the fuse-holder is the same so no current will flow through the red junction. However, LED3 is connected between the collectors of Q11, Q13 and Q14 and ground via a 47kΩ current-limiting resistor, so it will light up.

If fuse F1 blows, the collector voltages will drop to near 0V, so green LED3 will turn off but the full rail voltage will be across the fuse-holder and so the red LED2 will switch on. Similarly, LED5/LED4 indicates green/red when F2 is OK/blown.

These LEDs will also indicate if one of the two supply rails is missing (eg, due to a wiring fault); in this case, LED1 will probably still light up so it might not otherwise be obvious.

Clipping indicators

Now we can talk about the on-board clipping detector/indicator circuit. This involves just a few components and will indicates whenever the amplifier is driven into clipping, which may not be obviously audible.

It can drive an external LED mounted on the front panel of the amplifier. These components may be omitted if they are not required.

The clipping detector circuit is shown in Fig.2. Zener diode ZD1 derives a reference voltage 4.7V below the nominally 57V positive rail, ie, at about +52V. This is connected to the emitter of NPN transistor Q17. Its base is connected to the amplifier's output via a 100kΩ current-limiting resistor, with diode D6 preventing its base-emitter junction from being reverse-biased.

At the onset of clipping, the speaker voltage will rise above the +52V reference plus Q17's base-emitter voltage, ie, to about +53V. Q17 will switch on and sink current via LED4, a 1kΩ current-limiting resistor and isolating diode D5, lighting up clipping indicator LED6. As the reference voltage is relative to the positive rail, any variations in supply voltage will be accounted for.

ZD2, PNP transistor Q18 and diode D7 work in an identical manner for negative excursions.

However, Q18 drives LED6 via high-voltage NPN transistor Q19, which acts as a level shifter. The 100kΩ resistor in series with its collector limits the LED current to a similar level (1mA) despite the much higher rail voltage differential.

This is not the simplest clipping detector circuit, but it presents an almost completely linear load to the amplifier output, to minimise the possibility of any distortion due to its input load current.

It's connected to the driven end of L2 to give the amplifier the best chance to cancel out any non-linearities in the load it introduces.

Next month

Have we whetted your collective appetites? Next month, we will present the full details of performance and construction details.

Win a Microchip ATmega328PB Development Suite Bundle

EVERYDAY PRACTICAL ELECTRONICS is offering its readers the chance to win a Microchip ATmega328PB Development Suite Bundle. The ATmega328PB is a low-power CMOS 8-bit microcontroller based on the AVR enhanced RISC architecture. By executing powerful instructions in a single clock cycle, the ATmega328PB achieves throughputs close to 1MIPS per MHz.

The ATmega328PB is supported with a full suite of program and system development tools, and this bundle includes an ATmega328PB Xplained Mini evaluation kit, an ATATMEL-ICE development tool and an ATPOWERDEBUGGER Power Debugger kit. The ATmega328PB Xplained Mini (ATMEGA328PB-XMINI) evaluation kit is a hardware platform for evaluating the ATmega328PB microcontroller. It comes with a fully integrated debugger that provides seamless integration with Atmel Studio. The kit provides access to the features of the ATmega328PB MCU, enabling easy integration of the device into a custom design. The kit features two capacitive buttons for easy evaluation of the integrated QTouch® Peripheral Touch Controller (PTC).

The Atmel-ICE (ATATMEL-ICE) is a development tool for debugging and programming ARM Cortex-M based SAM and AVR microcontrollers with on-chip debug capability. It offers programming and on-chip debugging of all AVR 32-bit MCUs on both JTAG and aWire interfaces; programming and on-chip debugging of all AVR XMEGA family devices on both JTAG and PDI 2-wire interfaces; JTAG and SPI programming and debugging of all AVR 8-bit MCUs with OCD support on either JTAG or debugWIRE interfaces; programming and debugging of all SAM ARM Cortex-M based MCUs on both SWD and JTAG interfaces; and programming of all tinyAVR 8-bit MCUs with support for the TPI interface.

The Power Debugger kit (ATPOWERDEBUGGER) is a tool for debugging and programming AVR microcontrollers using UPDI, JTAG, PDI, debugWIRE, aWire , TPI or SPI target interfaces and ARM Cortex-M based SAM microcontrollers using JTAG or SWD target interfaces. In addition, the Power Debugger has two independent current-sensing channels for measuring and optimising the power consumption of a design. It also includes a CDC virtual COM port interface as well as Data Gateway Interface channels for streaming application data to the host computer from an SPI, USART, TWI or GPIO source. The Power Debugger is a CMSIS-DAP compatible debugger which works with Studio 7.0 or later, or other frontend software capable of connecting to a generic CMSIS-DAP unit. It streams power measurements and application debug data to Data Visualizer for real-time analysis.

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Mr Simon Perkins from SIPER Consulting Ltd, Newport, Gwent

Mr Edward Chase from Lemonpeel Controls Ltd, Micheldever, Hampshire

They each won a Microchip MCP9600 Evaluation Board, valued at £37.00

Arduino meets the ATtiny85 Microcontroller

No doubt you have seen heaps of interesting applications for Arduino boards. But what if you want to use some of those ideas in a design of your own using the Atmel ATtiny85 microcontroller? It's actually quite easy – and you can use Arduino software. Interested? Lawrence Billson takes up the story.

The ATtiny microcontrollers from Atmel are an ideal way to add simple programmable logic to your circuits. For example, the ATtiny85: it costs just a pound or two, and with only eight pins it is an easy way to get started by adding a microcontroller to your own design.

And if you are not a software guru, the chip can be programmed using the free Arduino IDE (integrated development environment), making short work of simple electronics projects.

The ATtiny85 chip has five general-purpose input-output (GPIO) pins. Three of them are capable of reading analogue voltages while the other two are capable of 'analogue' output – more on that later.

Other than writing your program to the chip's built-in Flash memory, all it really needs is a ground (0V) connection and a voltage of +2.7 to +5.5V on its V_{CC} pin (8).

With a few lines of code, the ATtiny85 can replace numerous analogue or digital ICs and give your design the flexibility of being reprogrammable.

Although the Arduino IDE allows you to program in C (technically C++), knowing the language isn't critical. With the very large 'community' built around the platform, many applications can be programmed using 'cut and paste' methods. Much of the Arduino code you find on the 'net will run on the ATtiny85 with little or no modification at all.

On paper, the ATtiny85 specs may seem underwhelming. It is an 8-bit micro with 8KB of rewritable Flash memory for storing and executing your program, 512 bytes of EEPROM for storing things like configuration or calibration variables from your project and another whopping 512 bytes of RAM.

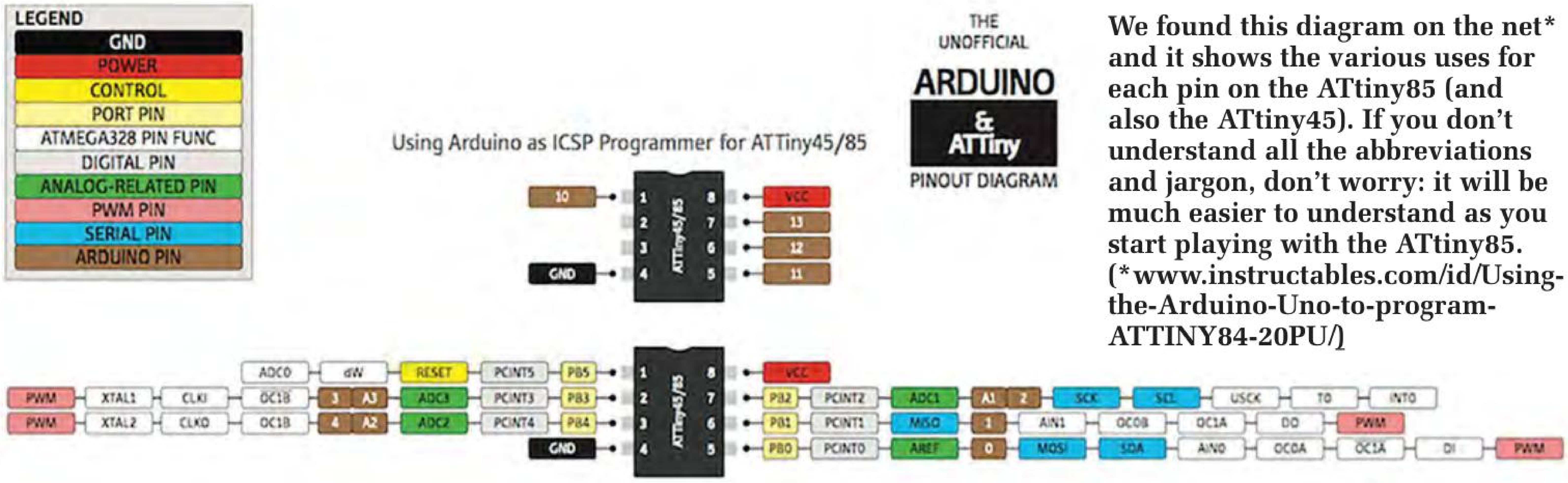
But don't let the meagre-sounding specs fool you. Using the freeware Arduino IDE, your code (or cut and paste effort) is transformed into tight, fast machine language using the built-in avr-gcc compiler.

In times gone past, a compiler for embedded processors was difficult to use and cost thousands of dollars – a huge barrier to entry. As well as being free, the Arduino software hides all of the 'engine room' parts like the compiler, chip 'fuses' and linker scripts.

Although the Arduino IDE is tailored for Arduino (or clone) boards, with only a few minor tweaks, it'll program your ATtiny chips nicely.

Development history

The ATtiny85 is based around Atmel's AVR architecture. This began life as a project by two students from the University of Norway in 1996. They were looking to build a microcontroller that was based around Flash memory. Using Flash memory allows a microcontroller's code to be changed without needing to expose chips to UV light or replace external ROMs.


LEGEND
GND
POWER
CONTROL
PORT PIN
ATMEGA328 PIN FUNC
DIGITAL PIN
ANALOG-RELATED PIN
PWM PIN
SERIAL PIN
ARDUINO PIN
THE UNOFFICIAL
ARDUINO
&
ATTiny
PINOUT DIAGRAM
Using Arduino as ICSP Programmer for ATTiny45/85
10
GND
ATTiny45/85
VCC
13
12
11
ADC0
dW
RESET
PCINT5
PB5
PWM
XTAL1
CLKI
OC1B
3
A3
ADC3
PCINT3
PB3
XTAL2
CLKO
4
A2
ADC2
PCINT4
PB4
PB2
PCINT2
ADC1
A1
2
SCK
SCL
USCK
T0
INT0
PB1
PCINT1
MISO
1
AIN1
OC0B
OC1A
DO
PB0
PCINT0
AREF
0
MOSI
SDA
AIN0
OC0A
DI

We found this diagram on the net* and it shows the various uses for each pin on the ATtiny85 (and also the ATtiny45). If you don't understand all the abbreviations and jargon, don't worry: it will be much easier to understand as you start playing with the ATtiny85. (*www.instructables.com/id/Using-the-Arduino-Uno-to-program-ATTINY84-20PU/)

Another advantage was that a product could be manufactured with a blank chip and programmed in the factory or field. If you pull apart many mass-produced products you may well find ICSP (In-Circuit Serial Programming) pads or pins on circuit boards for just this purpose.

Another problem the Norwegian students were attempting to solve was that of 'compiler bloat'. Chips like the Intel 8051, which was the dominant microcontroller at the time, use a complex instruction set (CISC) architecture.

While lending themselves to being programmed with assembly language, compiled languages would often become bloated as the compiler turned the program into machine language. This 'bloat' caused two problems: the code would become quite large and also quite slow to run.

As the AVR architecture took shape, the students worked closely with the authors of a professional compiler named 'IAR'. Being developed in parallel, the AVR evolved to be very good for running high-level compiled languages.

Classified as a RISC (reduced instruction set computer), it allows for most instructions to be executed in a single clock cycle and it hasn't changed much in the last 20 years.

Knowing that Flash memory was a key component in their design, the students from Norway knew they would need to take their chip design to a company that had experience making Flash memory. At the time, there were two – one based in Japan and Atmel in the United States. The Norwegians decided they spoke better English than Japanese and therefore approached Atmel.

Since their release in 1997, Atmel have sold hundreds of millions of AVRs. They are among the most popular microcontrollers being used by industry, and rival company Microchip (makers of the successful PIC microcontrollers) struck a deal to buy Atmel.

The ATtiny family is designed to be embedded into things. Tear apart a toaster or cordless drill and there's every chance you'll find one inside. They are available in DIP (through-hole) or a variety of surface-mount packages, and are equally at home on a breadboard or a mass-produced product.

In an interview on the excellent 'embedded.fm' podcast, Atmel's Andreas Eieland talks about millions of their smaller chips finding their way into home pregnancy testers, of all things!

So what can you do with it? Controlling things like stepper motors and servos is easy, as is gathering data from temperature or humidity sensors. The ATtiny85 shines at smaller automation jobs. Instead of a 555 timer or some logic gates, I'll often grab an ATtiny85 for the same job. As a rule of thumb, if the application has only a couple of inputs and outputs, it might be a good choice.

If your application needs more pins or support for more complicated programs, the Micromite or larger AVR chips may be a better choice.

Getting started – what you'll need

You will need an AVR-specific ICSP programmer. Usually in the form of a USB-attached gizmo, the ICSP allows the Arduino software on your computer to write its compiled program into the memory of your chip. The Freetronics unit will do the job well – see below.

As its name implies, the ICSP allows you to program your chip while it's in circuit. But this is not really practical in the case of the ATtiny85 since most of the I/O pins are used by the ICSP and this will limit what you can connect to them. So it's best to program the chip on a breadboard before embedding it into your circuit.

The 6-way connector that's standard on typical ICSPs isn't particularly breadboard-friendly. So we will make up a simple 6-pin header as an adaptor to connect it to a breadboard.

You'll also need a computer (laptop or desktop) on which to write your programs – any PC that runs Windows, Linux of Mac OSX will be fine. The Arduino IDE can be freely downloaded from: **arduino.cc**. Other than that, you'll need some ATtiny85 chips and you're ready to get started.

Your first ATtiny85 project

We start with the simple circuit shown in Fig.1. It uses four of the ATtiny85's I/O pins to connect to the ICSP header socket and one of the remaining I/O pins to drive an LED.

The first program you will use will simply flash that LED, and that's all. But you have to start somewhere. The circuit of Fig.1 needs to be made using a small breadboard and we have shown the component layout in Fig.2. So get your parts and a breadboard together!

Note that you will need to solder six insulated wires to a 6-pin DIL header and that will provide the connection to the ICSP programmer.

Now you need to program the ATtiny85. Begin by downloading and installing the latest release of the Arduino IDE. Be sure to say 'yes' to installing all of the recommended drivers that are included with it.

The Arduino software comes ready to work with their officially branded boards. As we'll be using it to program an ATtiny85 chip, we'll need to include support for it. You'll only need to do this once.

Once Arduino is installed, open the Preferences window and find the section for 'Additional Boards Manager URLs' – paste in **https://raw.githubusercontent.com/damellis/ATtiny/ide-1.6.x-boards-manager/package=damellis=ATtiny=index.json** and click OK.

Under the 'Tools' menu, select 'Board:' , then click on 'Boards Manager'. Type ATtiny in the search box. Select the ATtiny library by David A. Mellis, and click 'Install'.

From now on, your Arduino IDE will know about the ATtiny85 chips and be ready to program them.

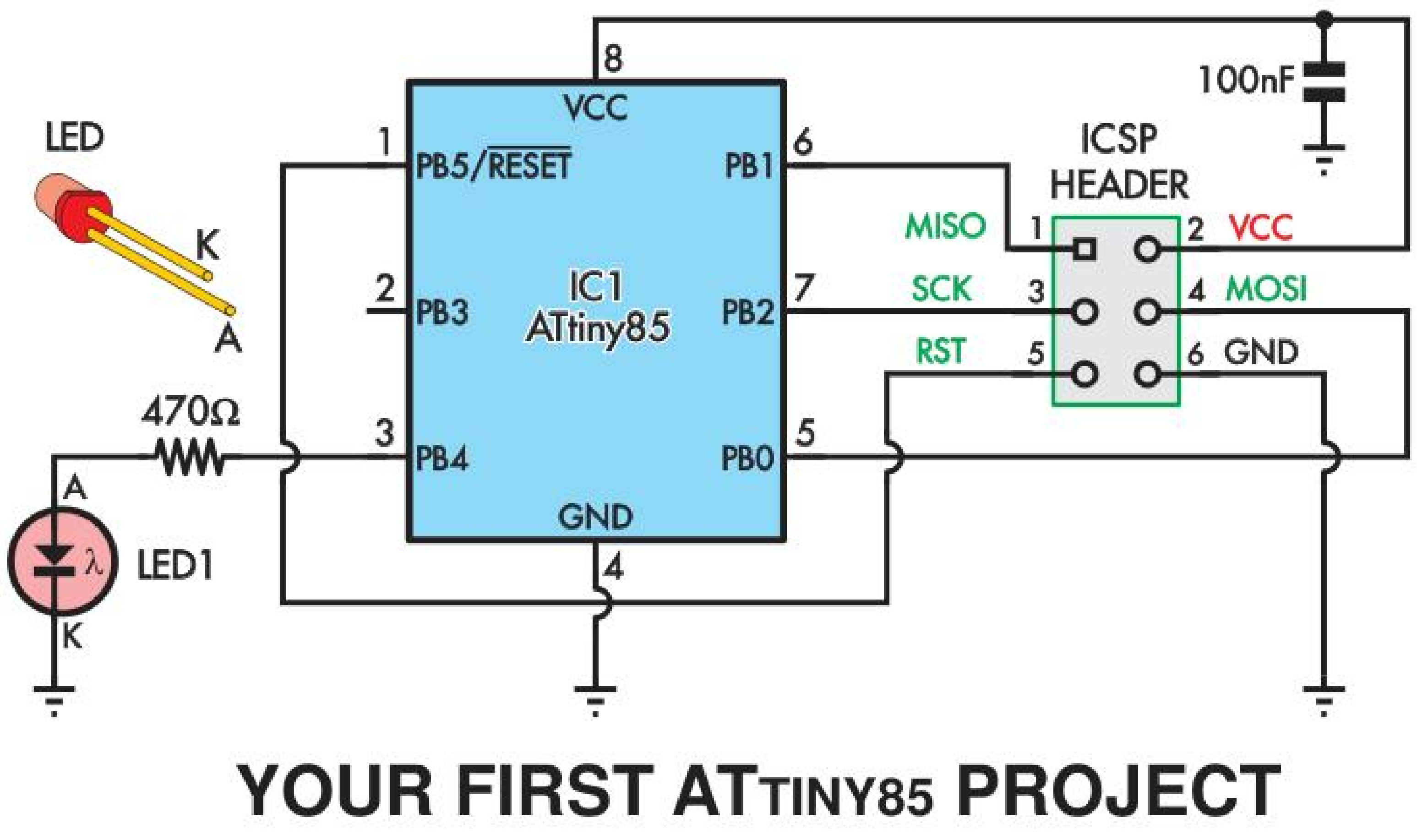
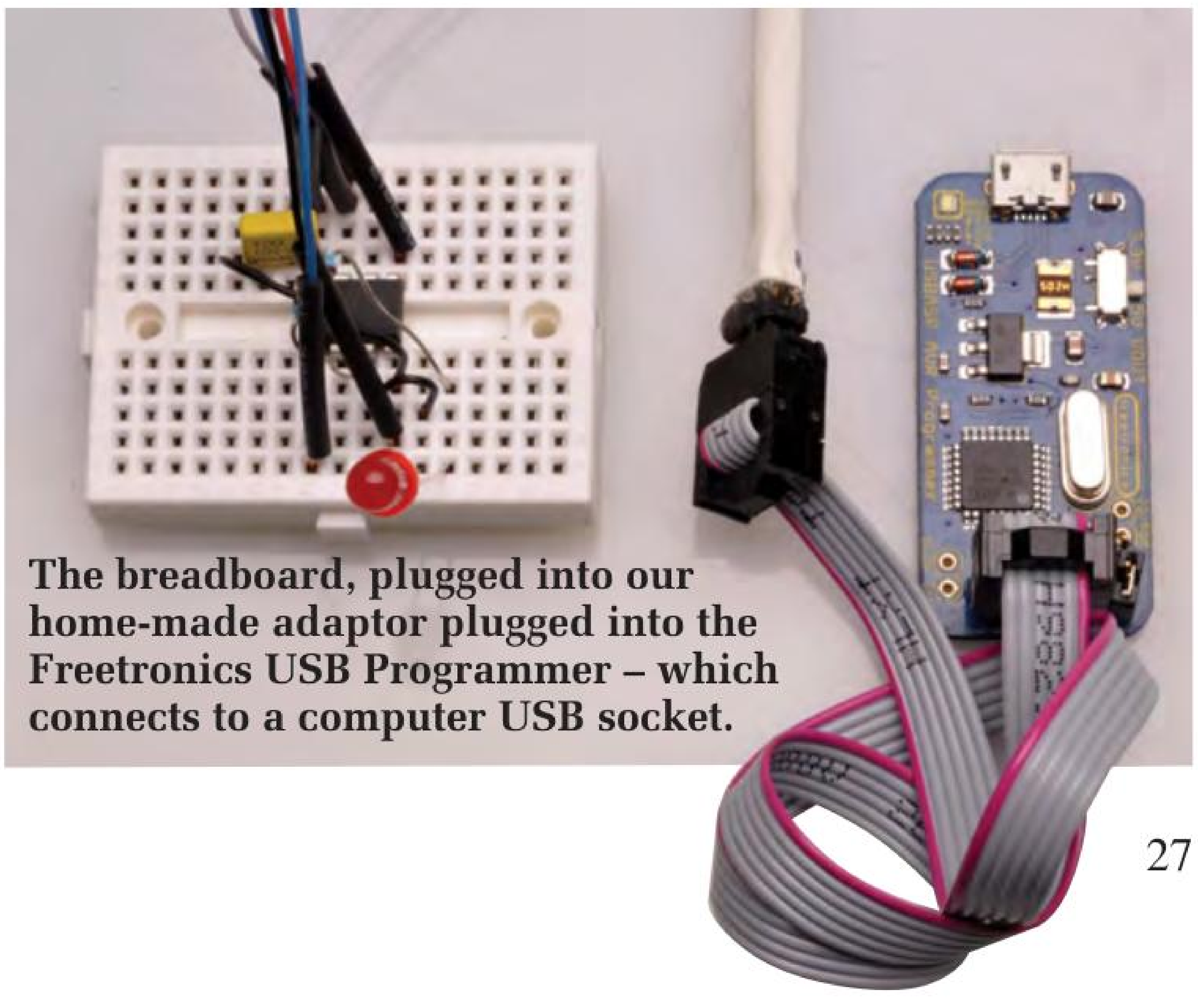


Fig.1: one chip, one LED and one resistor – you can hardly go wrong! At right is the layout on a mini breadboard.



The breadboard, plugged into our home-made adaptor plugged into the Freetronics USB Programmer – which connects to a computer USB socket.

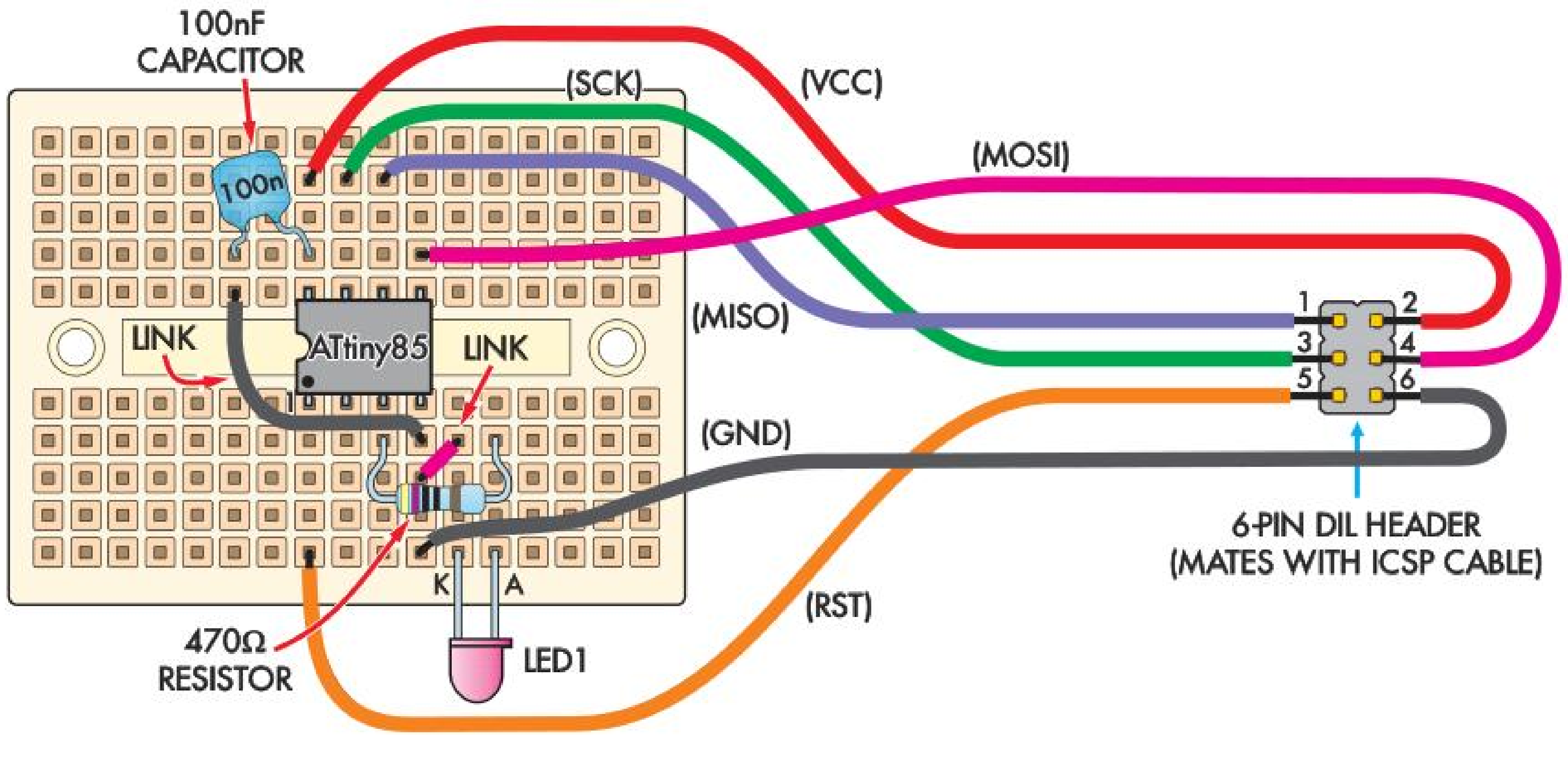
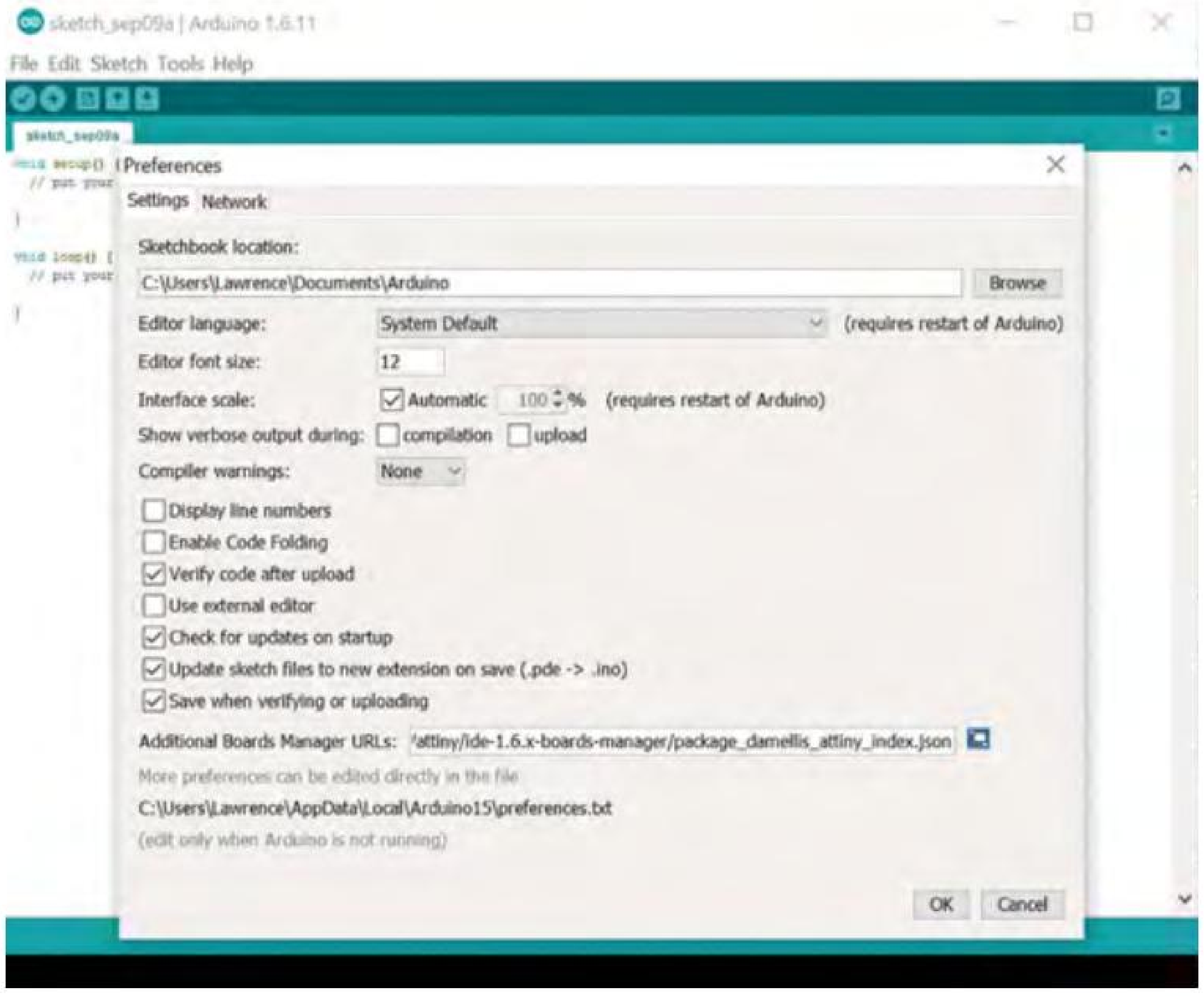

100nF CAPACITOR
100n
(SCK)
(VCC)
(MOSI)
LINK
ATtiny85
LINK
(MISO)
1
2
3
4
5
6
(GND)
6-PIN DIL HEADER (MATES WITH ICSP CABLE)
(RST)
K
A
470Ω RESISTOR
LED1

Fig.2: here's the breadboard layout for the *Flashing LED* project overleaf (Fig.1), along with the wiring for a 6-pin DIL header for programming.


sketch_sep09a | Arduino 1.6.11
File Edit Sketch Tools Help
sketch_sep09a
Preferences
Settings
Network
Browse
OK
Cancel

Sketchbook location: C:\Users\Lawrence\Documents\Arduino

Editor language: System Default (requires restart of Arduino)

Editor font size: 12

Interface scale: ☑ Automatic 100 % (requires restart of Arduino)

Show verbose output during: ☐ compilation ☐ upload

Compiler warnings: None

☐ Display line numbers

☐ Enable Code Folding

☑ Verify code after upload

☐ Use external editor

☑ Check for updates on startup

☑ Update sketch files to new extension on save (.pde -> .ino)

☑ Save when verifying or uploading

Additional Boards Manager URLs: /attiny/ide-1.6.x-boards-manager/package_damellis_attiny_index.json

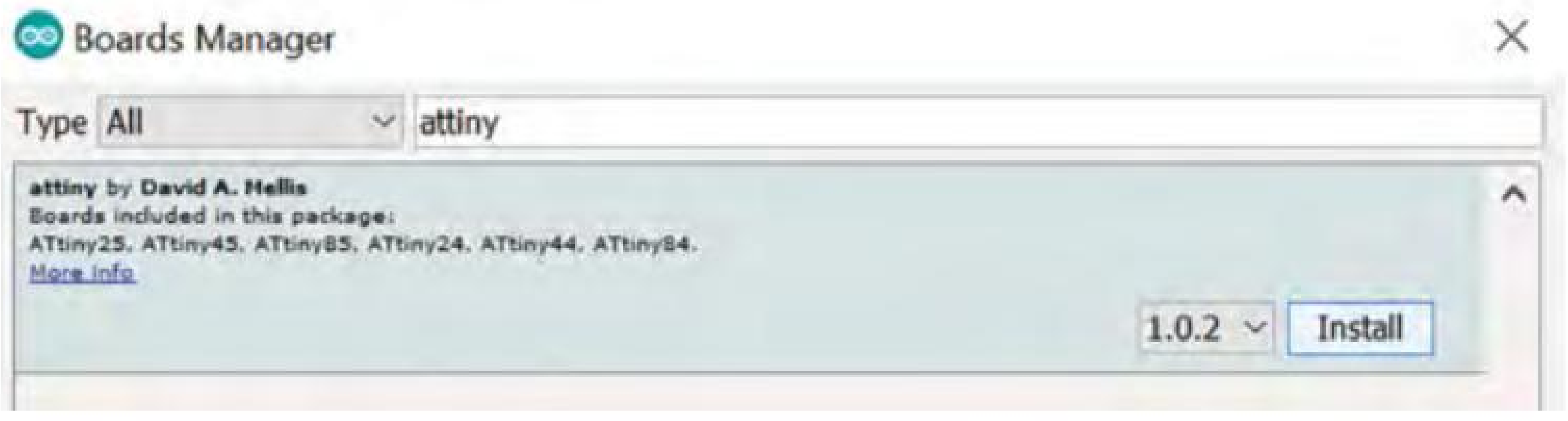
More preferences can be edited directly in the file

C:\Users\Lawrence\AppData\Local\Arduino15\preferences.txt

(edit only when Arduino is not running)

You'll need to tell Arduino about the chip we want to program. Under the 'Tools' menu, select 'Board <Name>' and you'll now see 'ATtiny' as an option. Select this. You must now go back in and give it some more details – in this example set:

Board - ATtiny
Processor - ATtiny85
Clock - 8MHz (internal)


Boards Manager
Type All
More info
Install

attiny

attiny by David A. Mellis

Boards included in this package:

ATtiny25, ATtiny45, ATtiny85, ATtiny24, ATtiny44, ATtiny84.

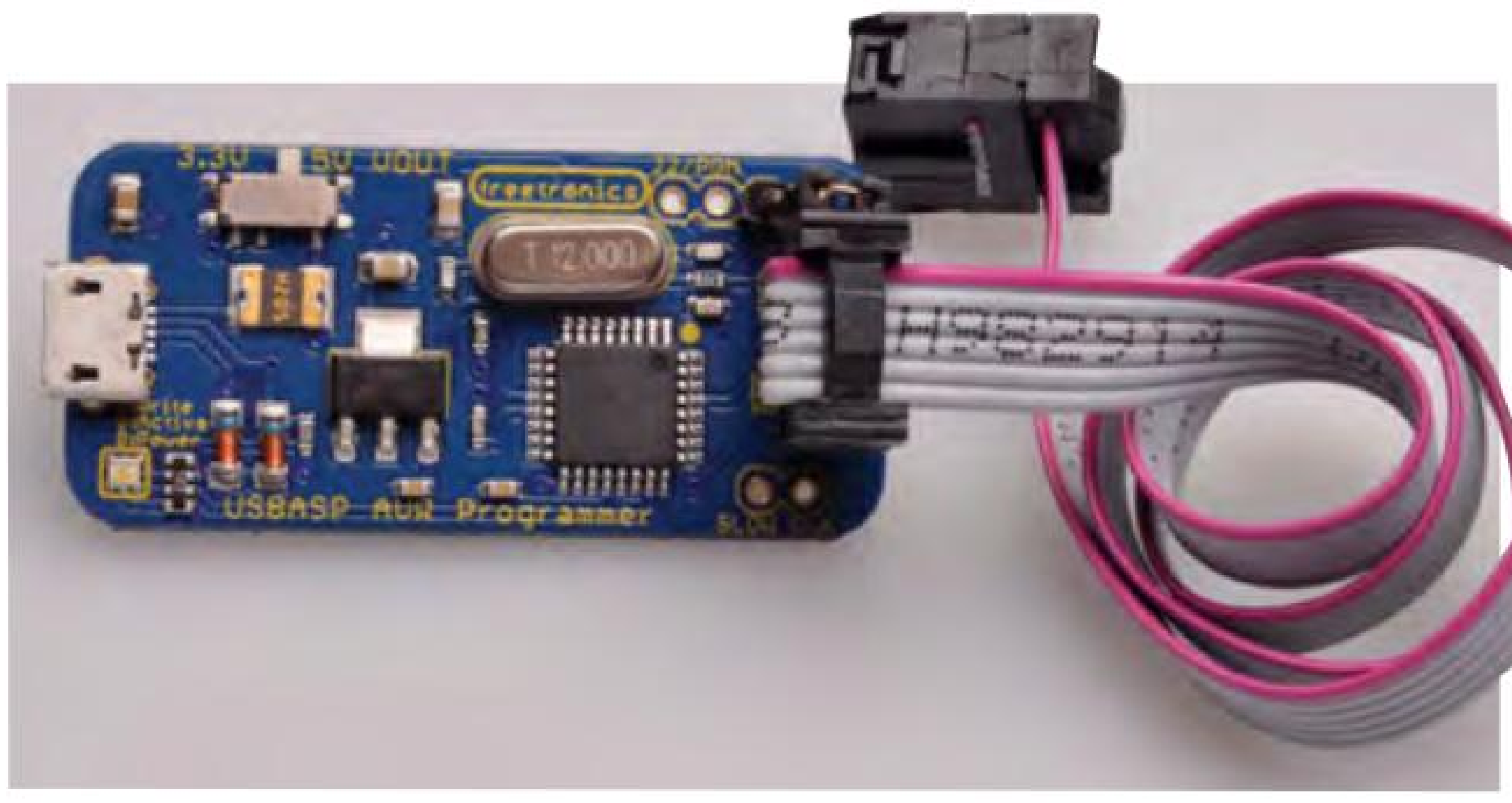
1.0.2

Be sure to select the internal clock. If you accidentally select an external clock your ATtiny85 can't be programmed unless you connect an external crystal.

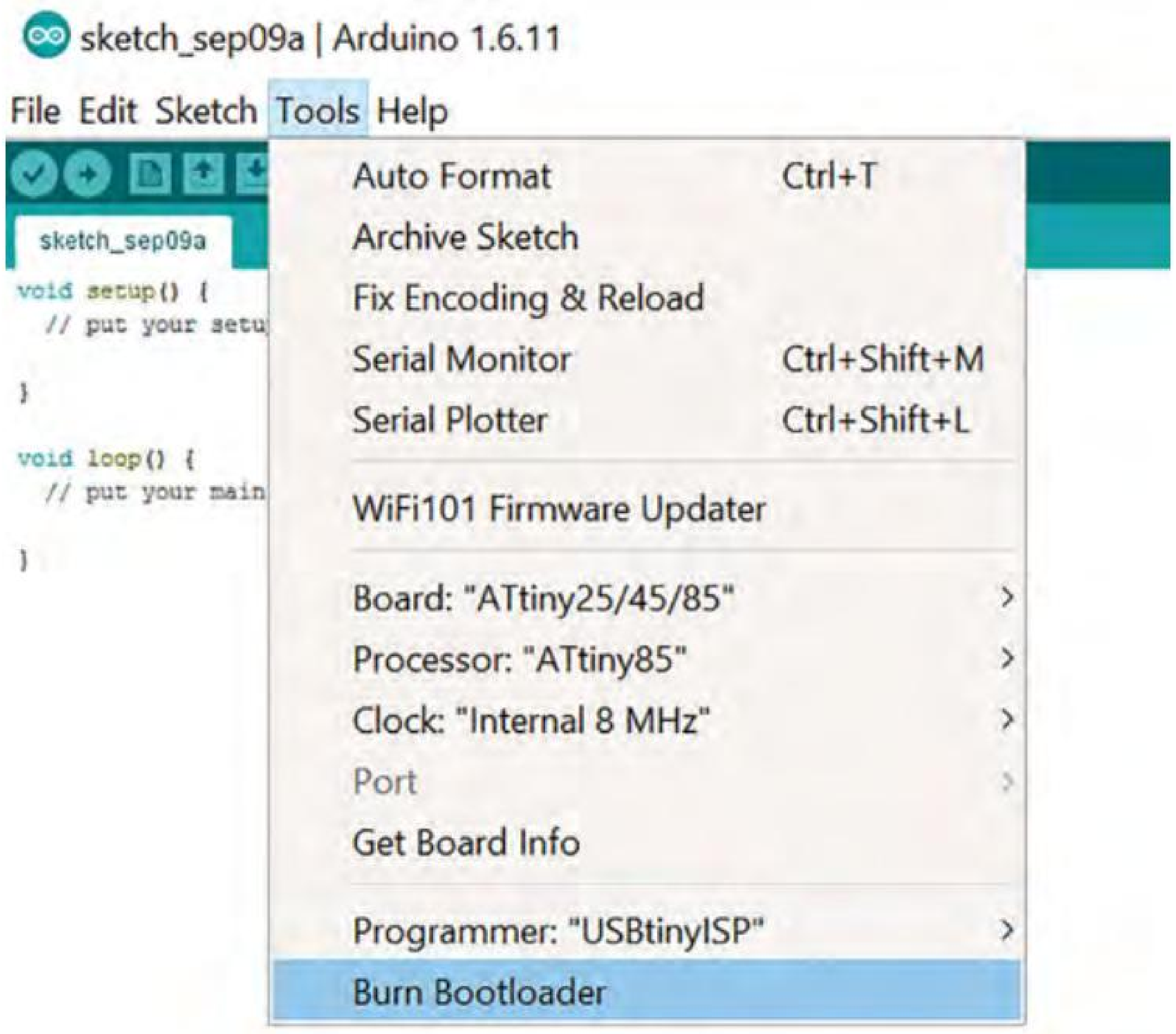
Now we need to tell Arduino what type of ICSP we'll be using. For the Freetronics XC4237, select 'USBasp'. Next, go to 'File', select 'Examples', 'Basics', and open 'Blink'.

The blink program normally tries to blink an LED connected to pin 13. But your ATtiny85 doesn't have quite that many! We have connected our LED to pin 4 (as in Fig.1), so you will need to change all of the references from '13' to '4'.

MISO connects to MISO, MOSI connects to MOSI. Some programmers won't supply any power to the board so you may also need to connect up a power supply or batteries. Other programmers may have a jumper marked V_{OUT} which you can short, thus powering your board from the ICSP. Check with a multimeter to verify your V_{CC} line is between 2.5 and 5.5V.


3.3V 5V VOUT
freetronics
USBASP AVR Programmer

Freetronics USB ICSP Programmer for AVR and Arduino. The six-pin socket on the end of the IDE cable mates with the 6-pin ICSP header pin 'plug' we will show you how to make later. This board then plugs into your PC via the micro-USB socket (left edge) and enables you to program the ATtiny85. (www.freetronics.com/usbasp).


sketch_sep09a | Arduino 1.6.11
File Edit Sketch Tools Help
sketch_sep09a
void setup() {
// put your setu
}
void loop() {
// put your main
}
Auto Format Ctrl+T
Archive Sketch
Fix Encoding & Reload
Serial Monitor Ctrl+Shift+M
Serial Plotter Ctrl+Shift+L
WiFi101 Firmware Updater
Board: "ATtiny25/45/85"
Processor: "ATtiny85"
Clock: "Internal 8 MHz"
Port
Get Board Info
Programmer: "USBtinyISP"
Burn Bootloader

For each new chip, you'll need to set its fuses. This tells the chip how to behave before it starts running any programs (eg, to use the 8MHz internal oscillator). Click on 'Tools' then 'Burn Bootloader'. Keep an eye out for error messages.

If all has gone well so far, it's time to write your code to the chip. Connect your ICSP programmer to the 6-pin header from the breadboard and connect the programmer to your PC. Holding down shift, click on the green arrow. This will compile your code and write it to the chip using the ICSP programmer.

If all has gone well, you'll have a blinking LED on your breadboard. Congratulations.

LED strobe

Our next circuit and program is for a simple LED strobe light. You have a wide choice of high-brightness LEDs of various colours for this job, but I chose a Jansjo 2W LED lamp from Ikea. It comes with a handy plugpack power supply, to provide the LED with 4.5V DC.

Our ATtiny85 can modulate with an N-channel FET and the circuit is shown in Fig.3. Pin 4 of the ATtiny85 drives the gate of the MOSFET, whereas in the previous circuit it just drove an LED via a 470Ω current-limiting resistor. The software is 'Ikea_Strobe.ino'.

But before you wire up the strobe circuit on a breadboard, as shown in Fig.4, you have to load the strobe software into the ATtiny85 using the breadboard layout of Fig.2. In fact, we suggest you keep that Fig.2 breadboard as your dedicated ATtiny85 programmer.

Before uploading the strobe code, don't forget to 'burn bootloader' to your new chip to set its fuses. Once the fuses are set, you can upload your code.

The strobe software task is divided into 'start' and 'loop' sections. When power is first applied to the micro, the start section is executed – this sets pin 0 as an output and pin 4 as an analogue input.

The loop section is then executed. In this, the micro sets pin 0 high (switching on the MOSFET, allowing current to pass from the lamp to the power supply). The micro waits for 5ms and sets pin 0 low; turning off the lamp.

The micro then measures the voltage at the potentiometer wiper. Depending on the position of the potentiometer, the value measured will be between 0 and 1023. The micro then waits for that same number (ie, between 0 and 1023) of milliseconds, allowing the strobe to vary its 'off time'. As soon as this completes, the loop begins anew.

So having built the strobe breadboard of Fig.4, you can plug in your freshly programmed ATTtiny85 chip and you are ready to go.

Audio Thermometer

This project makes use of the DS18B20 digital thermometer chip (or probe). Rather than displaying the temperature as a number, it plays a tone corresponding to the relative temperature it measures.

The DS18B20 is available in different package types – most commonly a TO-92 which looks just like a small transistor. It's also available in a waterproof probe suitable for immersion into liquids up to about 120°C.

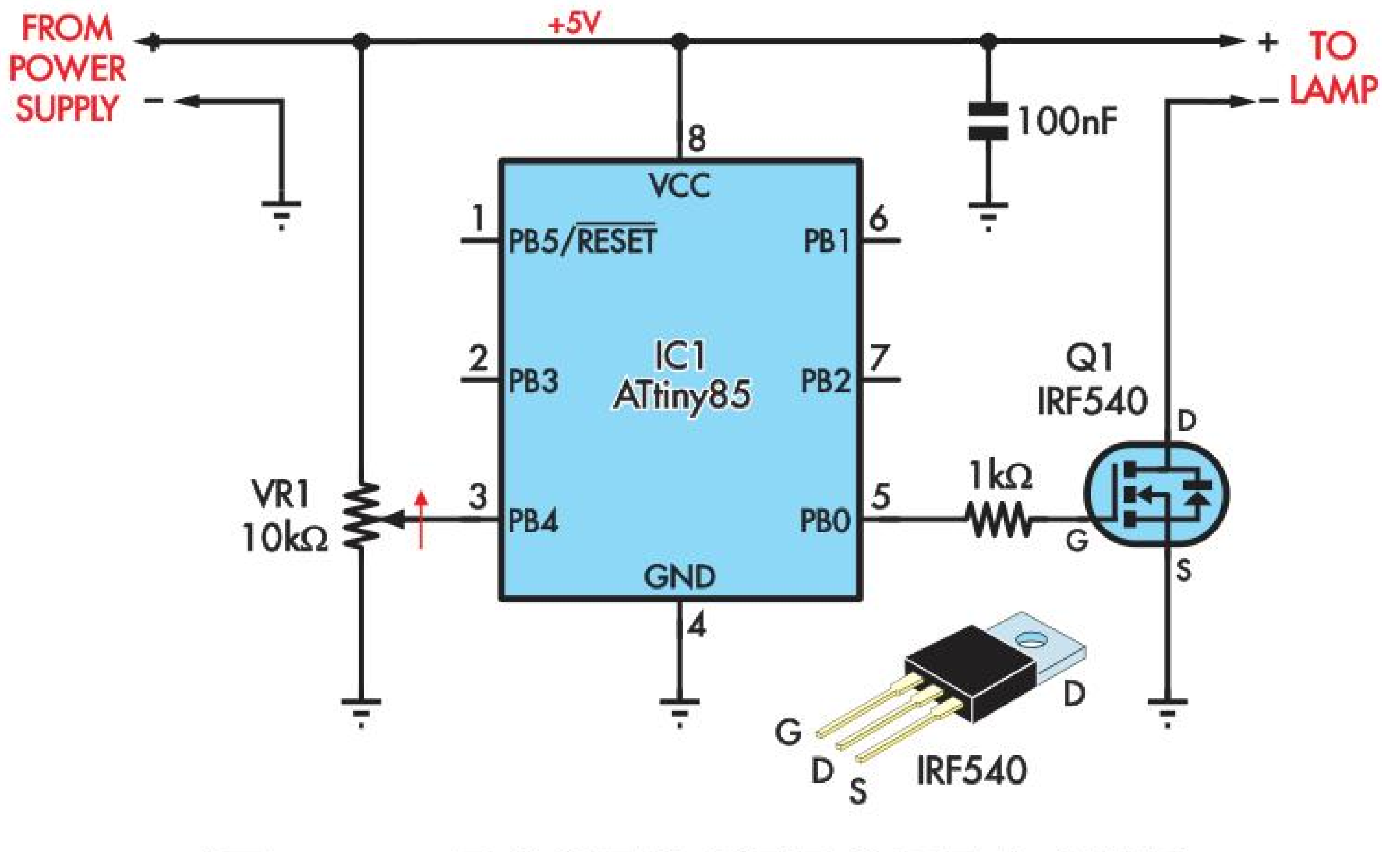
The circuit of the *Audio Thermometer* is shown in Fig.5 and the breadboard layout is Fig.6.

In this case we are using a 9V battery to power the circuit and this is reduced to 5V for the ATtiny85 and the DS18B20 thermometer.

The data line from the DS18B20 is fed into the PB3 input, pin 3 and also pulled high with a 4.7kΩ resistor.

As with most Arduino programs, the *Audio Thermometer* code is divided into the 'Start' and 'Loop' sections. An external library of functions is also loaded, to communicate with the DS18B20 thermometer. We simply tell the library which pin it's connected to, and request a temperature reading whenever we want.

The 'Start' routine runs once as the chip is powered on. It initialises the DS18B20 and sets the PB1 pin (6) connected to the piezo to be an output. It also sets the pin connected to the potentiometer wiper as an analogue input – this is used to vary the range of the tones.



ATTINY85 BASED STROBE LAMP

Fig.3: instead of flashing an LED directly, the strobe circuit drives a MOSFET which in turn drives a more powerful LED. VR1 varies the rate of the flashing LED.

The 'Loop' function starts by requesting the temperature from the DS18B20. It then measures the analogue value from the potentiometer wiper. The temperature value (reported in °C) can go as low as –55°C. As we'll be turning it into a

ATtiny85 pin functions

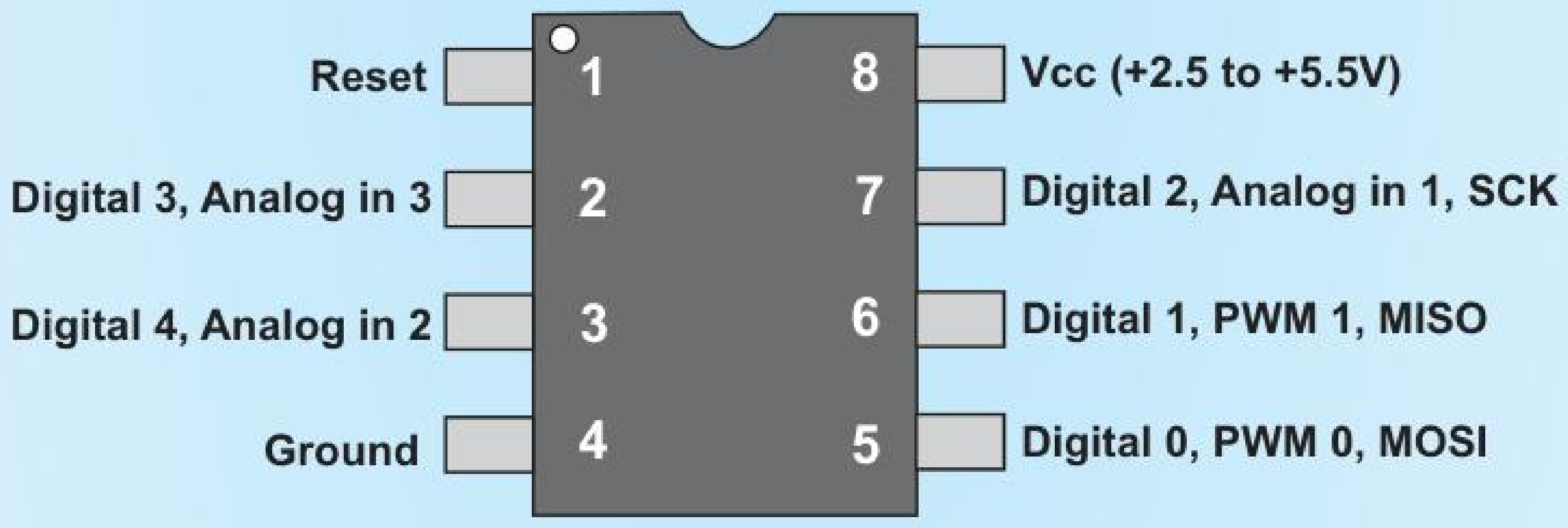
Digital: All of the I/O pins are capable of digital input and output. They can be set either high (VCC) or low (0V). They can also read a digital high or low.

Analog in: These pins are capable of reading a voltage of between 0 and your VCC voltage, providing a 10-bit number: 0V reads as '0' while VCC reads as '1023'. If you need to measure higher voltages, you can use a voltage divider circuit to reduce the voltage going into this pin.

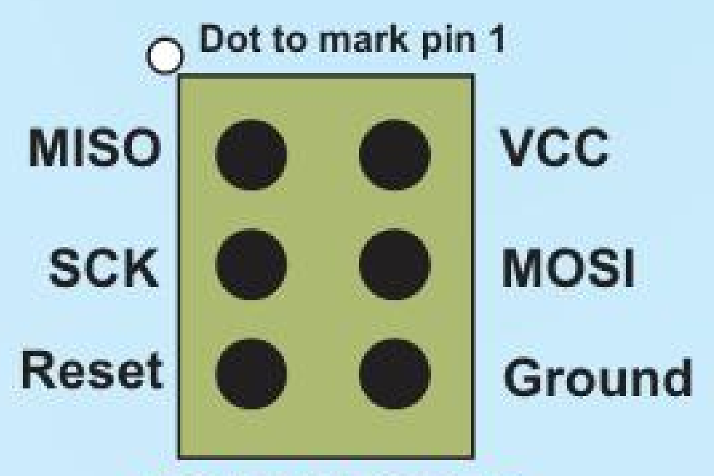
PWM: pulse-width modulation (PWM) output – these pins can simulate an analogue voltage output by using PWM. Instead of adjusting the voltage, they can send shorter or longer pulses, thereby changing the average voltage. For applications like motors or lights this works well. You can set these pins to an 8-bit value (ie, 0 to 255). When set to a value of 0, the pin has a 0% duty cycle and is equivalent to 0V. At 255, it has 100% duty cycle and is equivalent to your VCC voltage.

ICSP Pins: Connect your ICSP to these pins to program your chip. MISO and MOSI stand for 'master in, slave out' and 'master out, slave in' respectively. SCK is the 'chip select' that tells the chip the programmer is talking to it.

Reset: This is normally held high (ie, at 5V or whatever VCC is) by the chip. When pulled briefly to ground, the chip resets and starts running its program again.



PINS ON THE ATTiny85



ICSP PINOUTS
(Top view, looking at a programmer)

You'll note the pin numbers in software don't correspond with the physical pin numbers of the chip. This diagram will help translate between the software world and the real world.

frequency, we need to ensure it is a positive number. We do this by adding 60. We then multiply this number by the value of the pot to derive a frequency in hertz.

The tinyTone function is then called to output this frequency to the piezo speaker for 600ms before the loop restarts. As its name implies, tinyTone is a function that generates square wave tones. It does this by setting a pin high, waiting for a number of microseconds, then setting it low before waiting and repeating.

Want it to tell you the temperature in morse code? Want it to play different tones if the temperature is lower than 35.9° or above 36.7°C (armpit temperature)? With a little experimentation, either of these is quite simple.

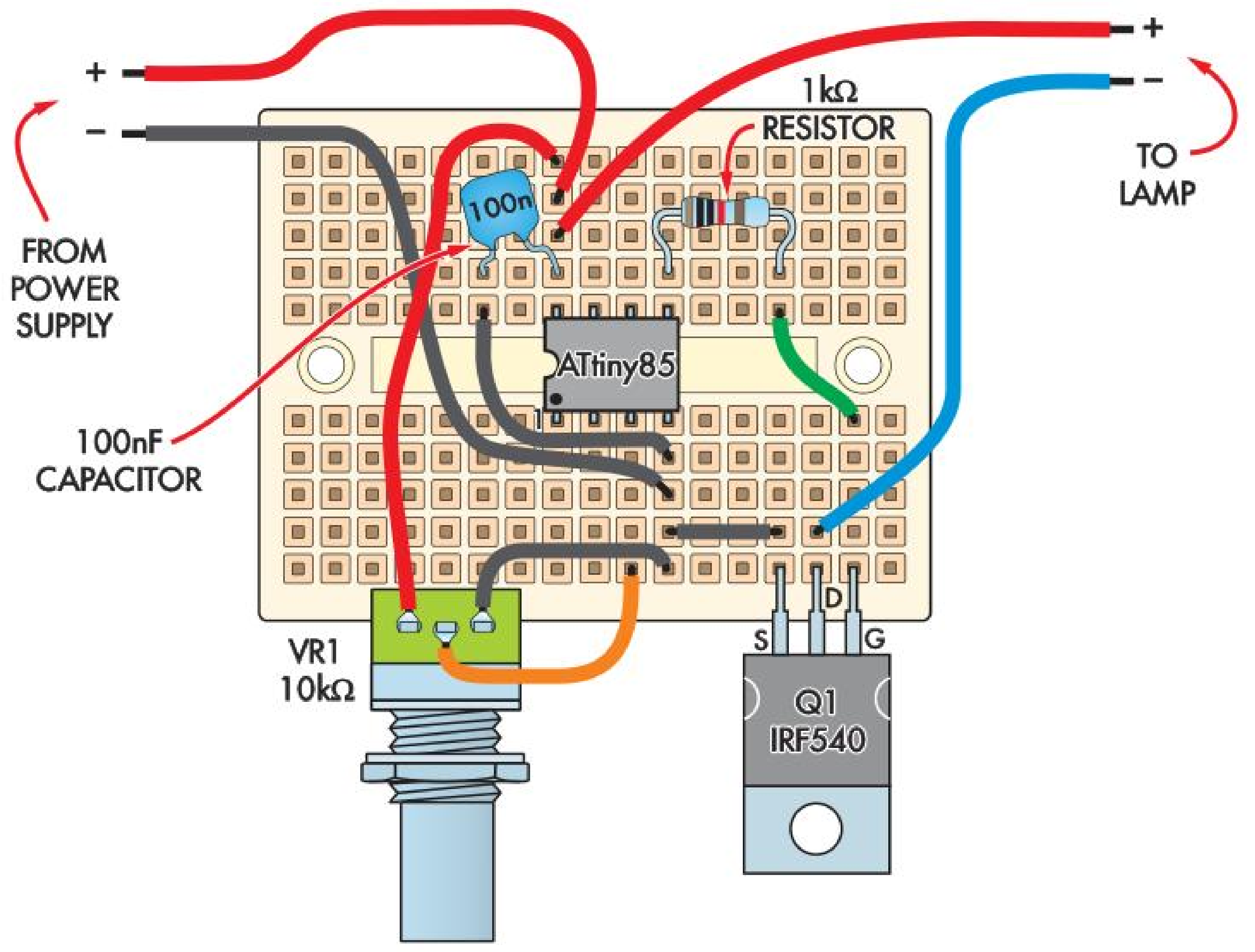
As before, you will need to program the ATtiny85 with the breadboard of Fig.1 and then transfer it to the breadboard layout of Fig.6.

Next steps

Looking under the Examples in the file menu, you'll see some easy-to-follow examples. Because the ATtiny85 doesn't have many pins or built in peripherals (like SPI or I^{2}C), some of those programs won't work, but they can still give you many examples to copy to your code.

Now is a good time to take a look at the Arduino community for other sources of inspiration and problem solving.

If you're having a problem with something, it's almost certain that you're not the first person to come across it and someone else will probably have solved it.


+
–
FROM POWER SUPPLY
1kΩ RESISTOR
100n
ATtiny85
100nF CAPACITOR
+
–
TO LAMP
VR1 10kΩ
S
D
G
Q1 IRF540

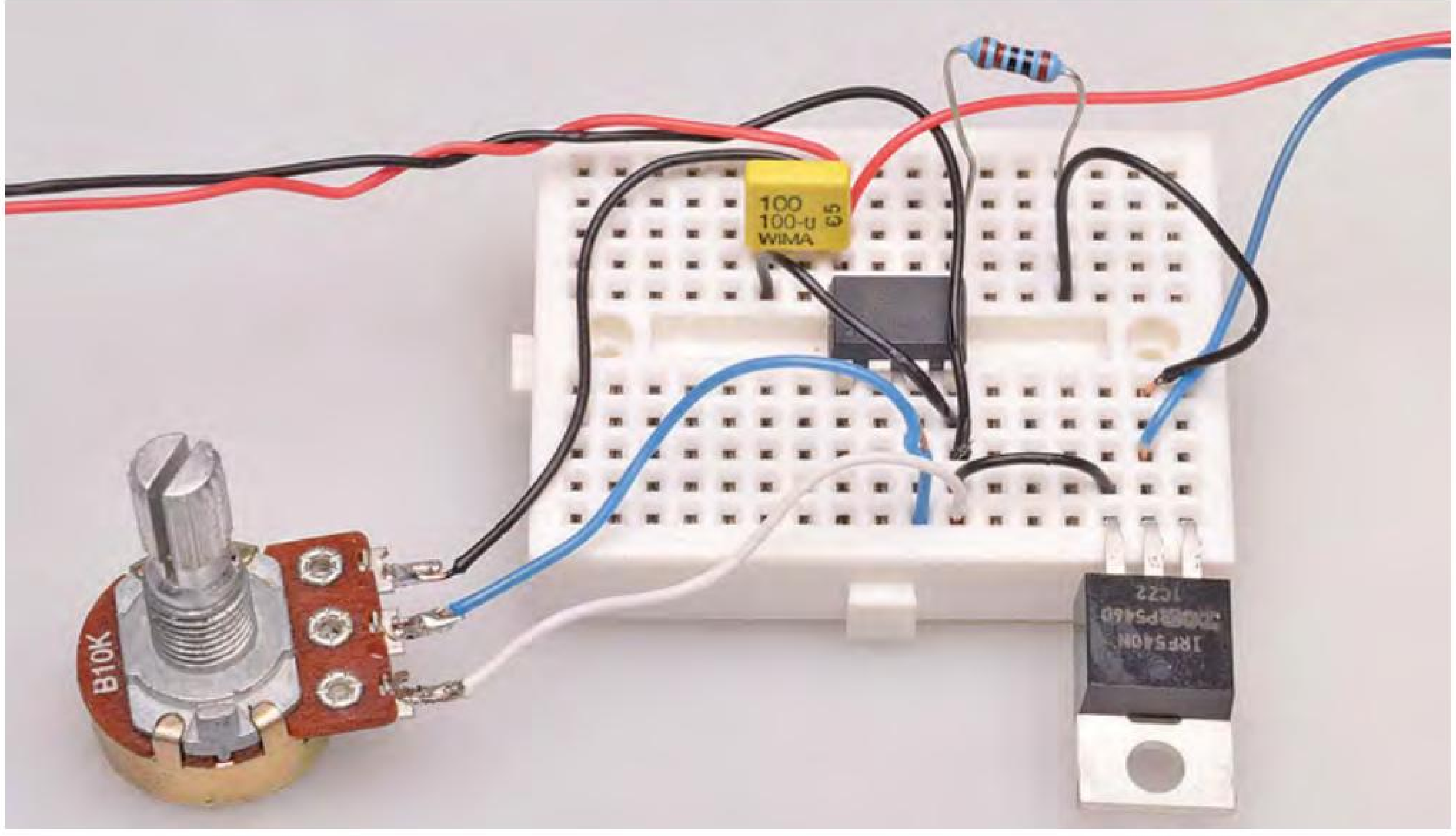

100
100-u
63
WIMA
B10K
IRF540N

Fig.4: breadboard layout (top) along with a matching photo (below) for the *ATtiny85 Strobe Lamp.* Remember that all of the north-south holes (in groups of 5) are connected inside the breadboard; all of the east-west holes are not.

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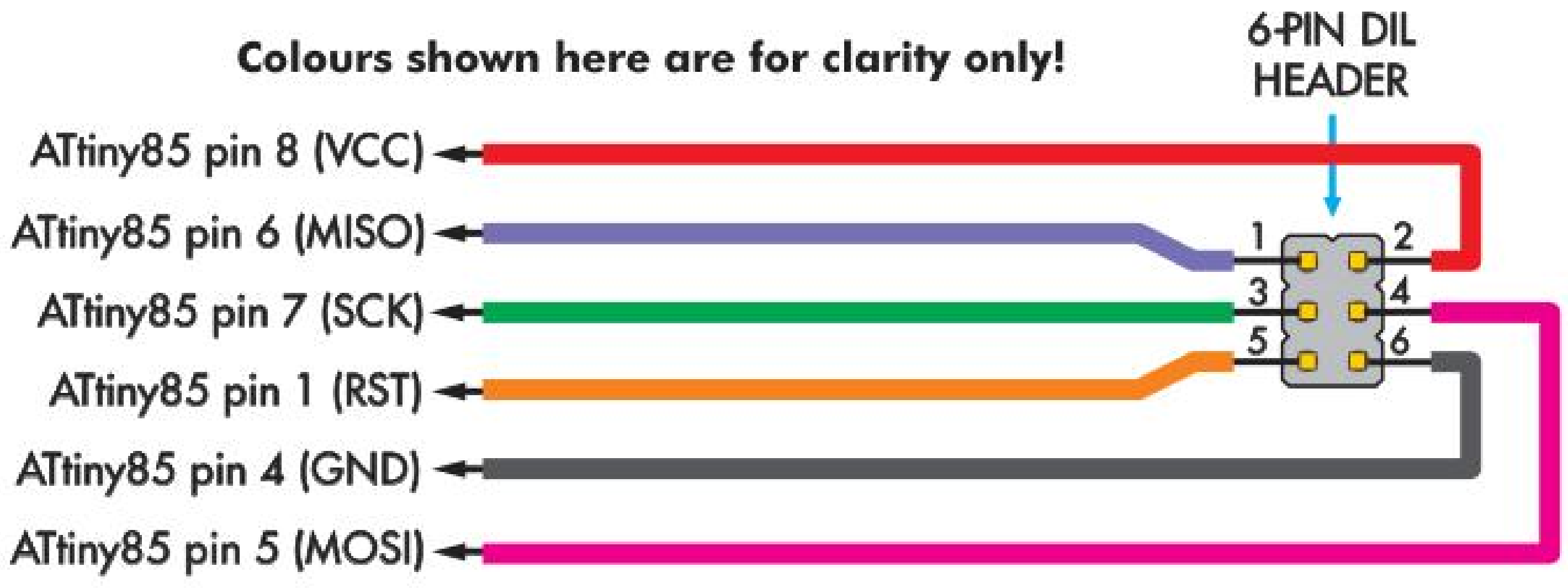
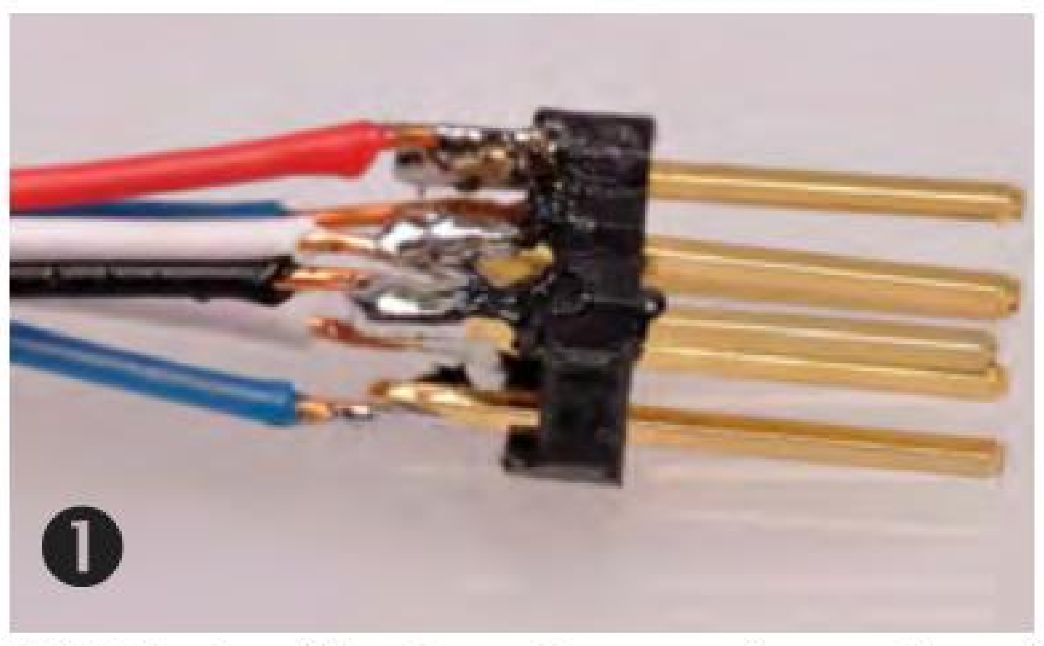
www.siliconchip.com.au

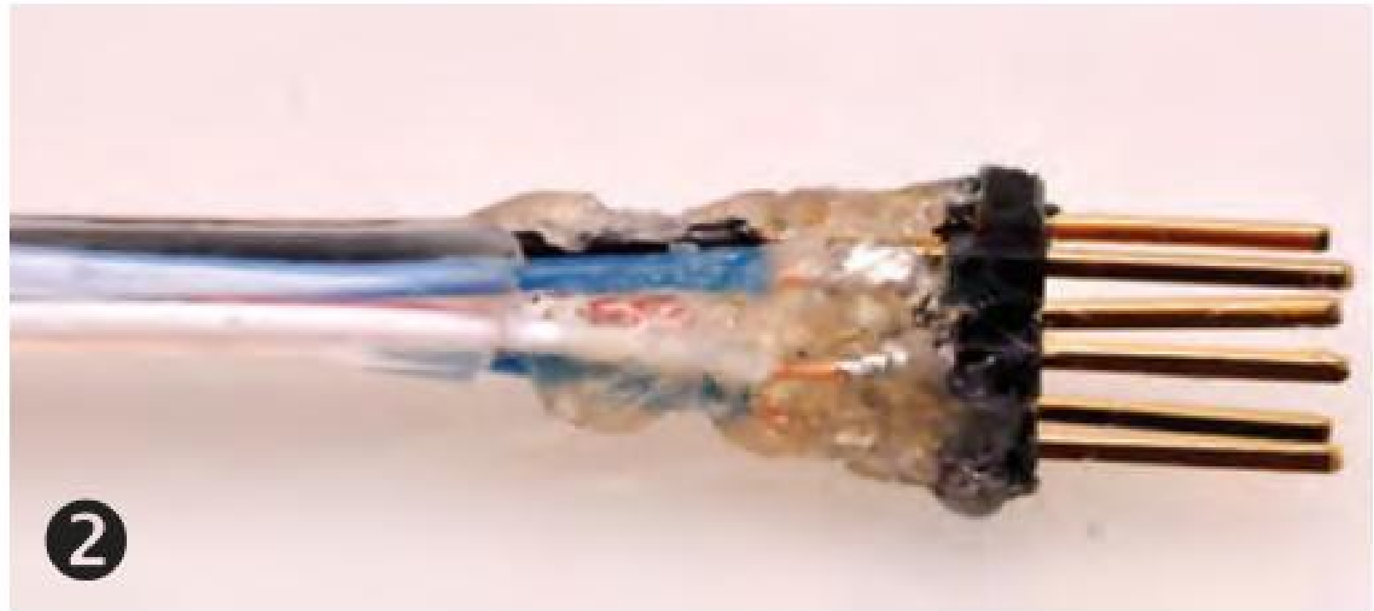
How to make the 6-way ICSP connector

It's easy to make a connector for the ICSP – all you need is a length of 2-way pin header (eg, Altronics P-5410) and carefully remove a 3-pin length. The wiring we used came from a length of 4-wire discarded telephone cable (yep, we never throw anything out!) It has colours of red and black (ideal for power) and blue and white (for everything else). You could also use female-male jumper leads and avoid some soldering.


Colours shown here are for clarity only!
6-PIN DIL HEADER
ATtiny85 pin 8 (VCC)
ATtiny85 pin 6 (MISO)
ATtiny85 pin 7 (SCK)
ATtiny85 pin 1 (RST)
ATtiny85 pin 4 (GND)
ATtiny85 pin 5 (MOSI)
1
2
3
4
5
6



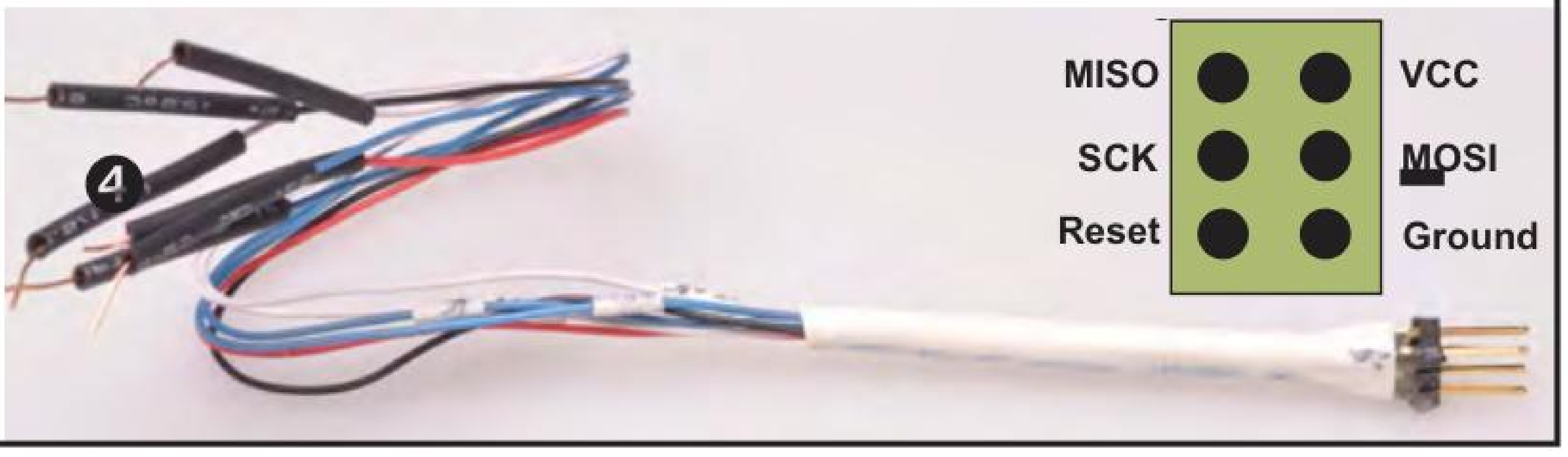
(1) Cut off a 3 x 2-way length of pin header and solder six wires to it. A red wire connects to the + terminal and a black to – (other colours can be what you have available).

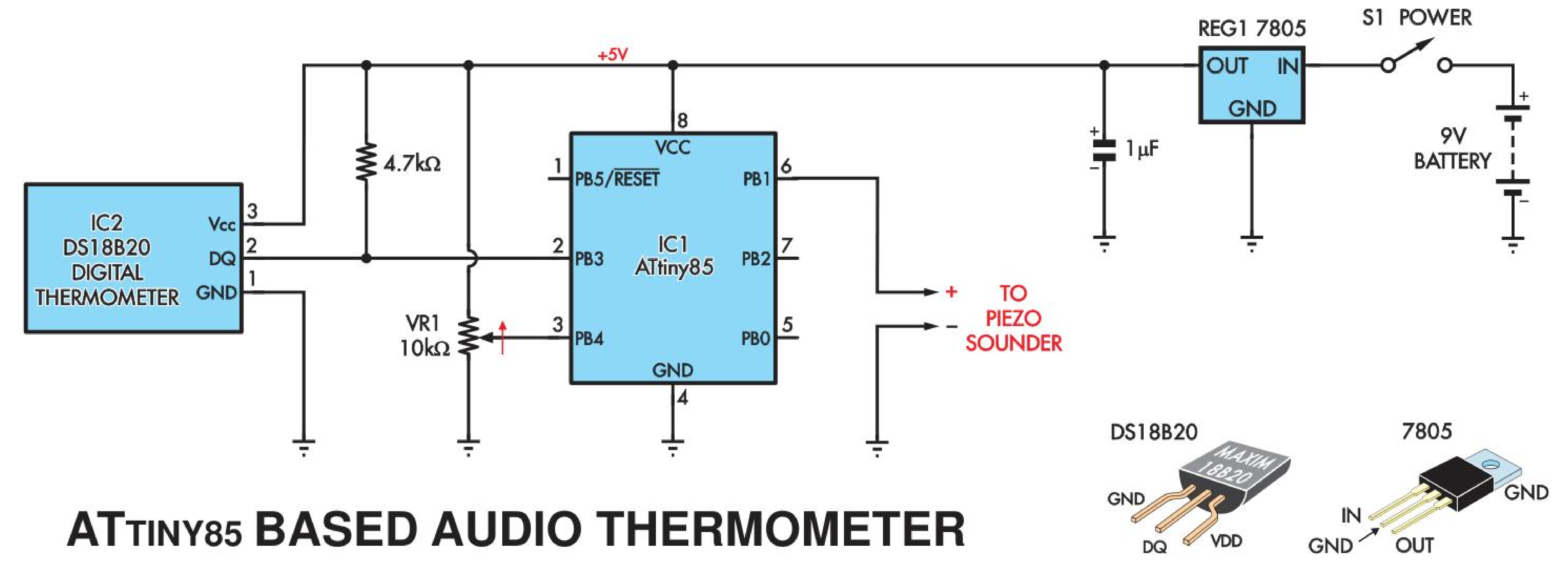


(2) Apply a glob of hot melt glue (or silicone sealant if you don't have hot melt) over the soldered pins and back up the wires to keep the wires in position when it is being used. Allow to dry.

(3) Cover with a length of heatshrink tubing, right down onto the glue. This will stop it trying to pull apart as it is inserted and removed from the socket.

(4) Slide some short lengths of white heatshrink over each wire towards the plug, and some longer lengths of heatshrink over the opposite ends of each wire to make them stiffer. With a multimeter, identify which pin goes to which wire and write it on the white heatshrink. Shrink all heatshrink . . . and it's finished!


MISO
VCC
SCK
MOSI
Reset
Ground


REG1 7805
S1 POWER
+5V
OUT
IN
GND
1µF
9V BATTERY
4.7kΩ
VCC
8
1
PB5/RESET
PB1
6
IC2 DS18B20 DIGITAL THERMOMETER
Vcc
DQ
GND
3
2
1
PB3
IC1 ATtiny85
PB2
7
VR1 10kΩ
PB4
PB0
5
GND
4
+
–
TO PIEZO SOUNDER
DS18B20
MAXIM 18B20
GND
DQ
VDD
7805
IN
GND
OUT
ATTINY85 BASED AUDIO THERMOMETER

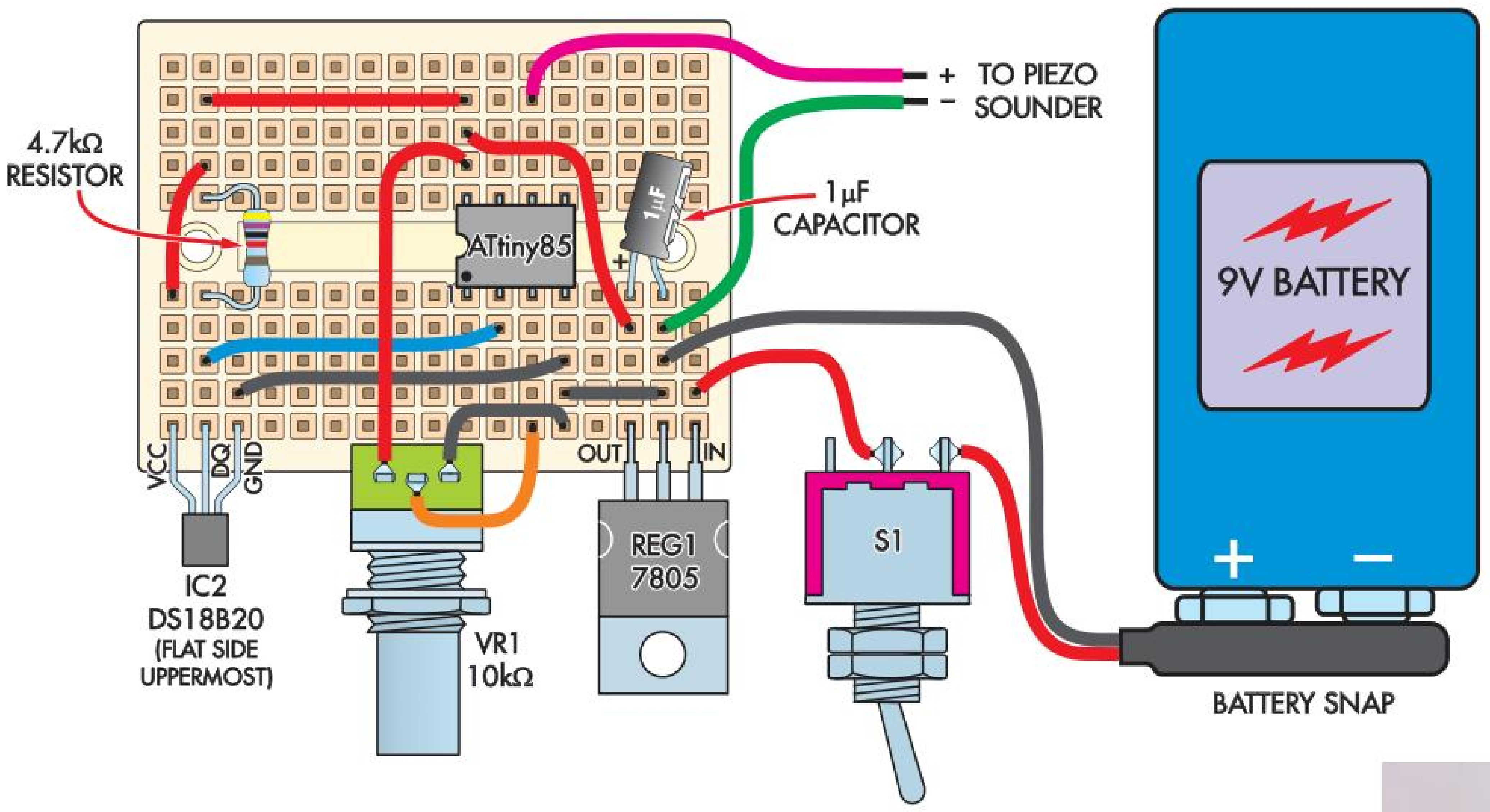
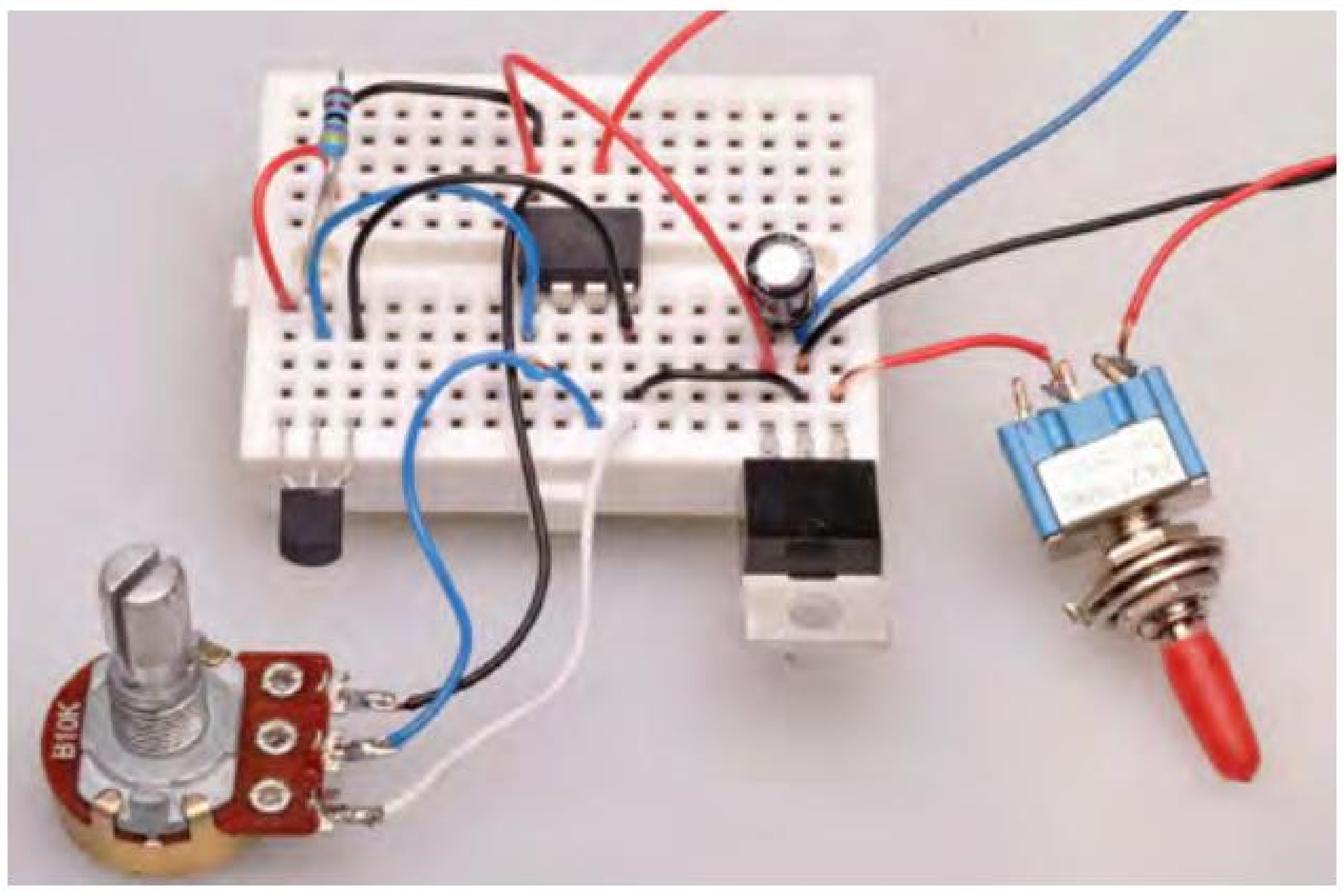

4.7kΩ RESISTOR
+ TO PIEZO
– SOUNDER
1µF CAPACITOR
ATtiny85
9V BATTERY
VCC
DQ
GND
OUT
IN
IC2 DS18B20 (FLAT SIDE UPPERMOST)
VR1 10kΩ
REG1 7805
S1
+
–
BATTERY SNAP

Fig.5 (above): the Thermometer uses a DS18B20, small solid-state digital thermometer chip, which will feed a number sequence to the ATtiny85 representing the temperature it is sensing. The ATtiny85 then generates a tone for the piezo sounder corresponding to the temperature.

Fig.6 (left): the breadboard layout for the audio thermometer. It's a little more complex so make sure the components and wire links are in the right place. You can also refer to the matching photograph (below).



References

www.atmel.com/images/doc0943.pdf – shows how to use ICSP with other things connected to the pins. Embedded.fm episode 15

http://embedded.fm/www.instructables.com/id/Using-the-Arduino-Uno-to-program-ATTINY84-20PU/ – not the exact chip we're using here, but gives a lot more information about programming the ATtiny series using Arduino.

Parts you will need

First of all, you need the Freetronics ICSP Programmer for Arduino, which you can buy on Freetronics' website (**www.freetronics.com.au**) for £12 plus shipping
See: **www.freetronics.com.au/blogs/news/8607215_**

It comes with a ribbon header cable (6-pin to 6-pin) and a short USB cable (type A to micro-B). And they'll throw in a mini protoboard for only £2 more – just what you need!

By the way, Freetronics also provide a PDF guide to using their programmer, which readers may wish to use in conjunction with the description provided above.

Other main parts (Not a complete list... These components will allow you to build any one of the projects here but some components are common to all three).

1 Atmel ATtiny85 microcontroller
1 DS18B20 digital thermometer chip
1 IRF540N N-channel MOSFET
1 7805 5V regulator
1 red LED
1 Jansjo 2W LED lamp and 4.5V DC plugpack from Ikea
1 1µF 10V electrolytic capacitor
1 100nF polyester capacitor
1 470Ω resistor
1 1kΩ resistor
1 4.7kΩ resistor
1 10kΩ potentiometer
1 x 2 pin DIN plug
1 x 2 pin DIN socket
1 x 8 pin IC Socket
6 300mm lengths single-core copper or tinned copper wire ('bell wire')
1 2x3-way DIL pin header (may to be cut down from larger – eg 2x10-way
(If not obtained above from Freetronics): 1 small breadboard (protoboard)

Download the required code (programs) from the *EPE* website (**www.epemag.com**).

EPE EVERYDAY PRACTICAL ELECTRONICS

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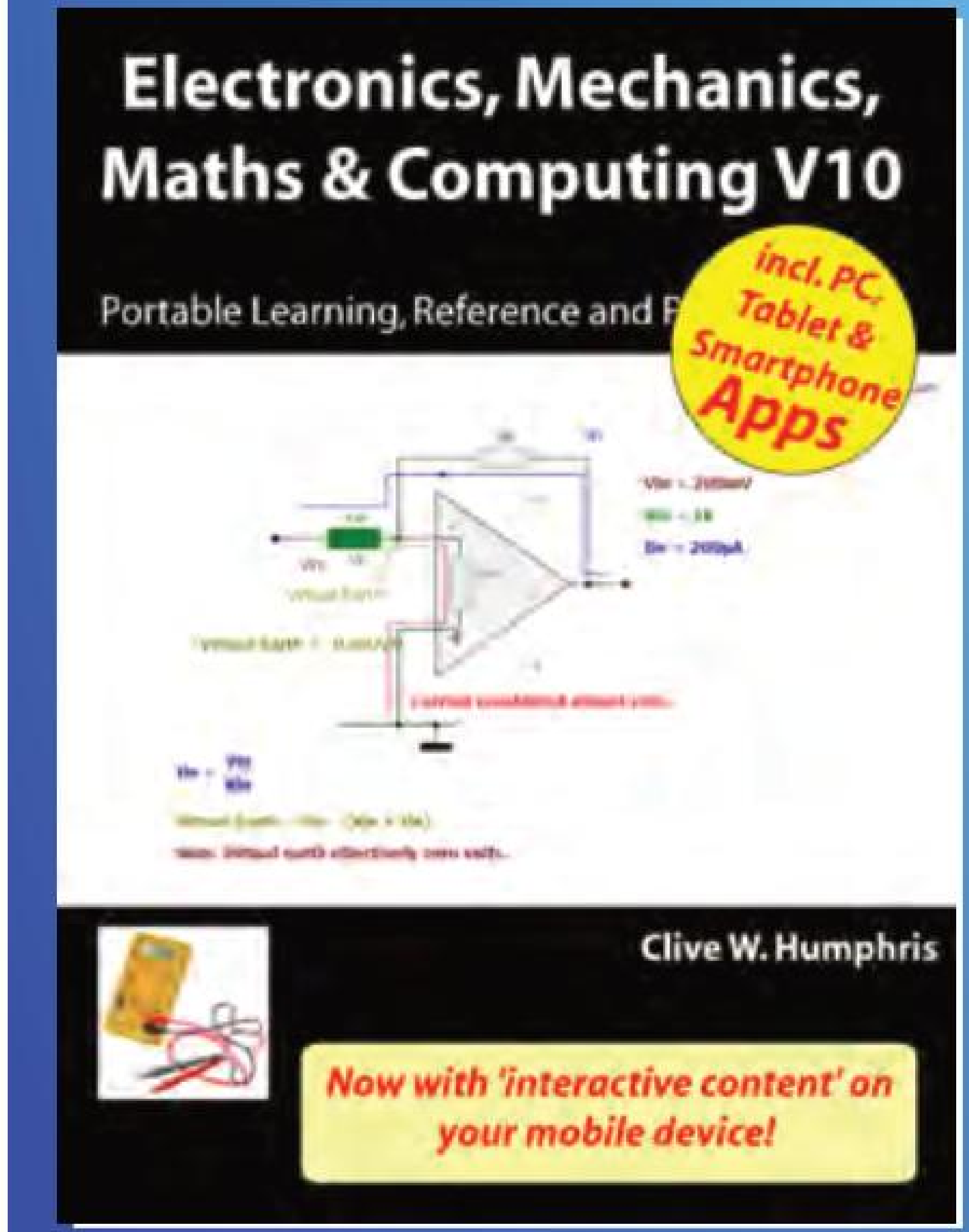
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The new standard components!

By JIM ROWE

Using Cheap Asian Electronic Modules Part 1

This is the first of a series of small articles which will help you take advantage of the wide range of handy pre-built electronic modules that are now available from Asia. This month, we review the DS3231 real-time clock (RTC), which is the perfect partner for popular microcontrollers like the Arduino or Micromite.

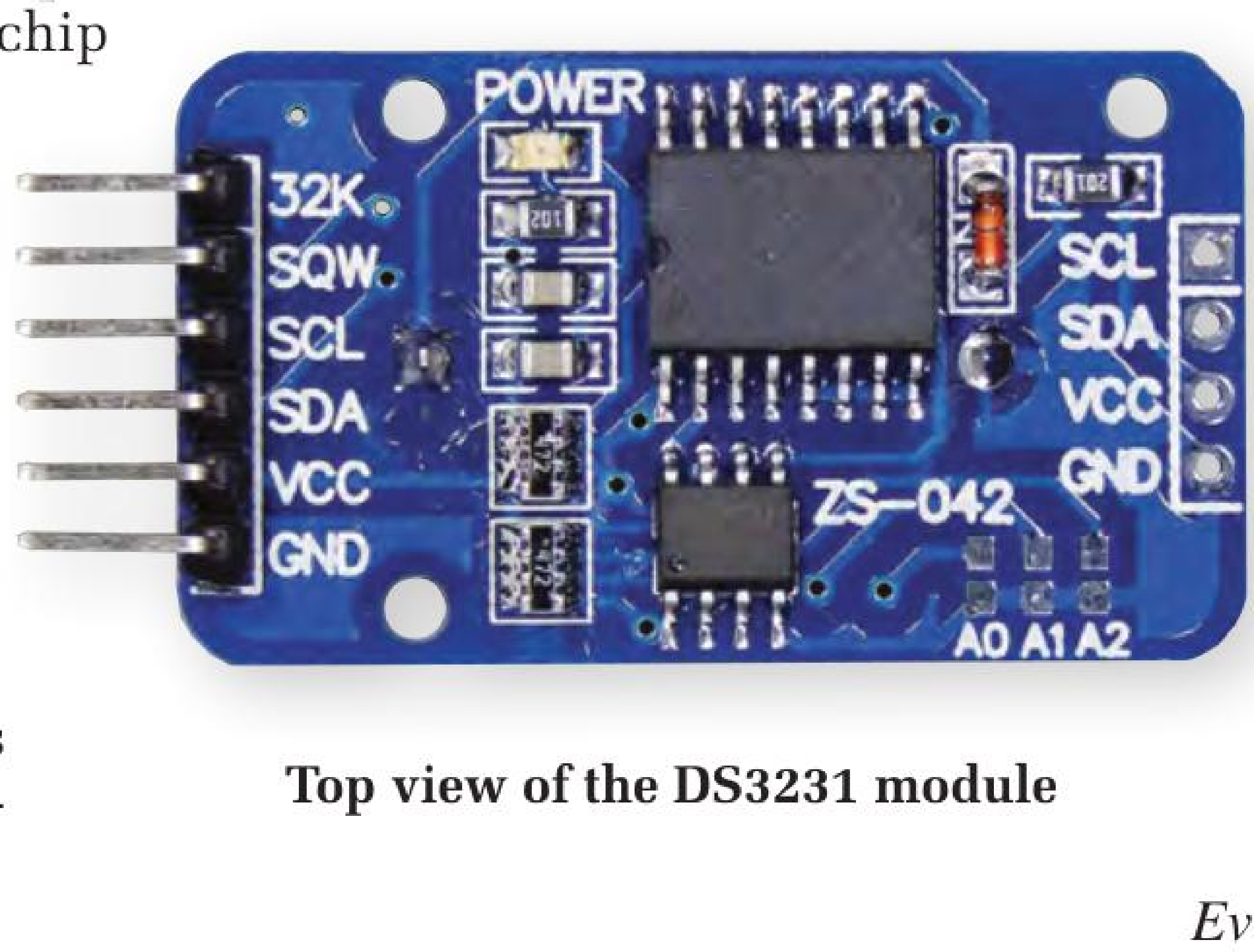
IF YOU'VE been reading *EPE* for a while now, you'll have noticed that small electronic modules have been creeping into our projects.

These are not just Micromite, Arduino or Raspberry Pi boards, but really small and low-cost modules including real-time clocks/calendars (RTC), USB-to-UART serial 'bridges', UHF data transmitters and receivers, DDS signal generators, OLED/LCD panels, touch-screen TFT LCDs, temperature/humidity sensors, microSD card interfaces and many more. They seem to be breeding like rabbits!

Many of these modules have sprung into life initially as 'peripherals' for baby micros like the Arduino (ie, shields) and Raspberry Pi. But most of them have a lot of other applications in circuits and designs using standard TTL or CMOS ICs, and even in designs using olde-worlde discrete transistors.

But the really big advantage of this new generation of pre-built modules is that most of them are surprisingly low in cost. In fact, with many of them, you'll find that the cost of a complete module is much less than the price you'd pay for the main IC chip used in them.

A prime example is the popular real-time clock/calendar module using Maxim's very accurate DS3231 RTC chip — plus a 24C32 4KB EEPROM, in most cases. Although the module is usually advertised as intended to be used with an Arduino, it has a standard I²C ('Inter-IC') interface and can actually be used with most other micros (we used it with the Micromite in our *Touchscreen Super Clock*).



Top view of the DS3231 module

So that's the rationale behind this series of articles on the new 'el cheapo' modules. They're readily available, often have many applications and they're usually much cheaper than building up the same circuits for yourself. As a result, they've now reached the status of being just standard circuit components. The Electronic Modules As Components or 'EMAC' revolution has begun!

Let's get the ball rolling by looking at real-time clock/calendar modules.

RTC modules

Probably the first low-cost RTC modules to appear were those based on the Philips/NXP PCF8563 chip, a low-power 8-pin CMOS device which has an I²C interface but needs an external 32.768kHz crystal. Modules based on the PCF8563 are still available at low cost from eBay or AliExpress, but they tend to be less popular than modules based on one of two newer Maxim chips: either the DS1307 or the DS3231.

Like the PCF8563, the DS1307 needs an external 32kHz crystal. However, it also has a built-in power sense circuit which switches to a backup battery when it detects a power failure. It has 56 bytes of internal non-volatile SRAM and a standard I²C interface, making it compatible with just about every type of microcontroller module such as the Arduino or the Micromite.

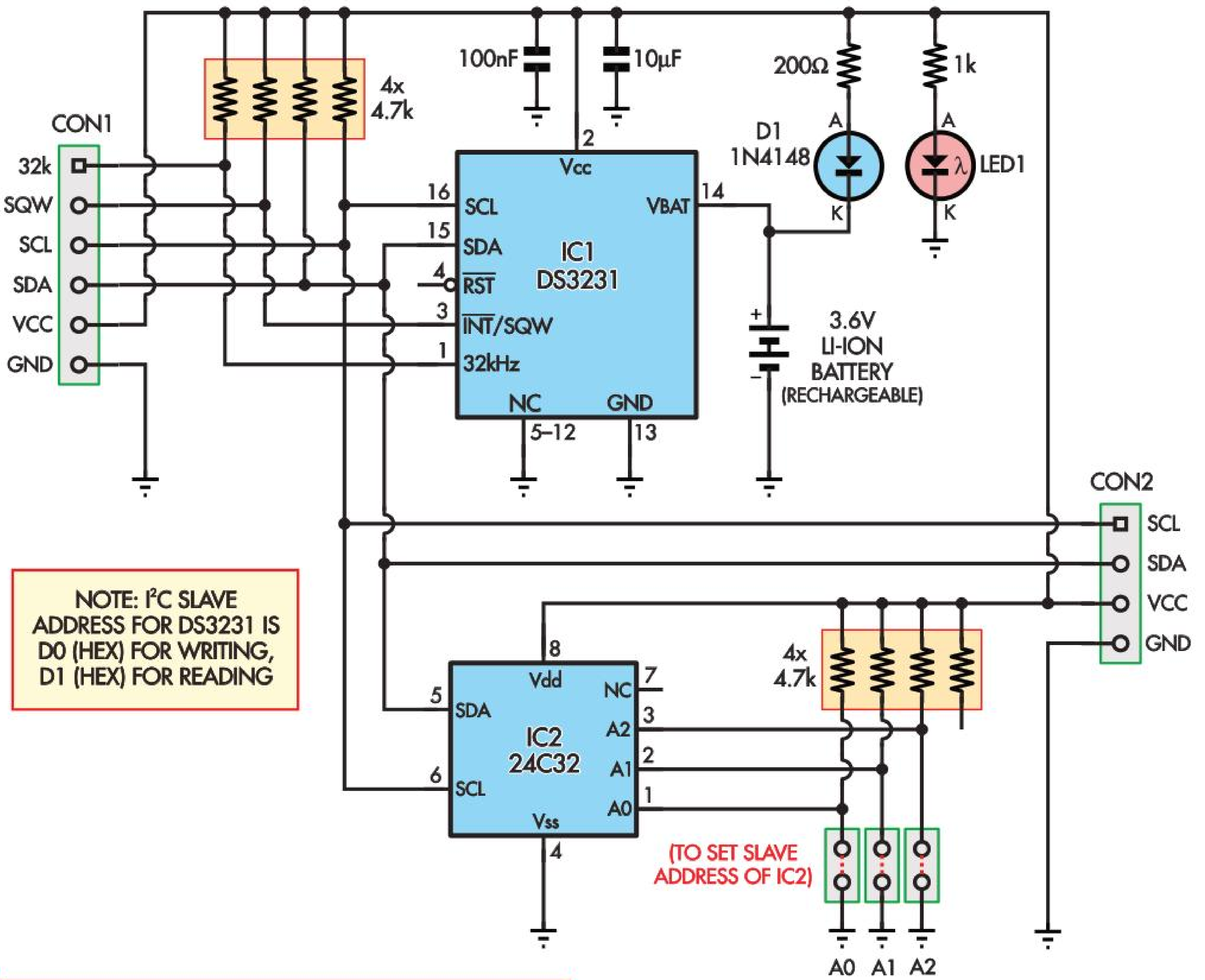
It does have one shortcoming, though: the time-keeping accuracy is inclined to drift a little with temperature and so it can vary by a few minutes a month.

Clock/calendar modules using the DS1307 tend to cost more than those using the PCF8563, but they often include extras like a DS18B20 temperature sensor and a 24C32 serial EEPROM (32Kbits = 4KB). This makes them quite attractive for applications where extreme accuracy isn't too critical.

But modules based on the DS3231 chip are currently the most popular, partly because the DS3231 has an on-chip temperature-compensated crystal oscillator and crystal.

It also includes an internal temperature-compensated voltage reference and comparator, both to maintain its own supply voltage and to automatically switch to a backup supply when necessary.

These features allow it to provide significantly higher timekeeping accuracy: better than ±2ppm between 0



I²C SLAVE ADDRESSES (HEX) FOR 24C32 EEPROM

MSD (FIXED)	A2	A1	A0	WRITE	READ
A	1	1	1	AE	AF
A	1	1	0	AC	AD
A	1	0	1	AA	AB
A	1	0	0	A8	A9
A	0	1	1	A6	A7
A	0	1	0	A4	A5
A	0	0	1	A2	A3
A	0	0	0	A0	A1

← DEFAULT ADDRESS (NO LINKS ON PADS FOR A0, A1 OR A2)

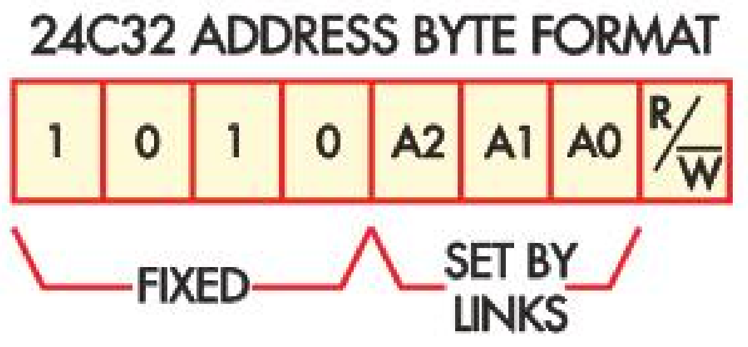


Fig.1: complete circuit for the DS3231-based RTC module. Both CON1 and CON2 provide serial bus and power connections, allowing extra devices to be connected. Note that the I^{2}C bus should have only one set of pull-up resistors.

and 40°C, or ±2 minutes per year for a temperature range of –40°C to +85°C. Its single shortcoming compared with the DS1307 is that it lacks the internal non-volatile SRAM.

Despite the advantages offered by the DS3231, modules using it tend to cost no more than those based on the DS1307 or the PCF8563. And this applies for modules like the one shown in the pictures, which also includes a 24C32 serial EEPROM.

As mentioned earlier, this is the RTC module that has been used in a number of recent projects like the *Touchscreen Super Clock* and the *Micromite Explore 100*, so it's the one we'll now concentrate on.

DS3231 RTC

As shown in the circuit diagram of Fig.1, there isn't a great deal in this module apart from the DS3231 chip itself (IC1), its 3.6V backup battery and the 24C32 serial EEPROM (IC2). We'll discuss the rest of the components and circuitry shortly after we've looked at what's inside the DS3231.

Its compact 16-pin small outline (SO) SMD package contains an I^{2}C data bus interface, address decoding for the 18 internal time, date and control registers, a temperature sensor and a power control circuit which can swing over to the backup battery when the supply voltage (V_{CC}) fails. Its block diagram is shown in Fig.2.

Then there's a complete temperature-compensated 32.768kHz crystal oscillator (TCXO), followed by a frequency divider chain and all of the time (seconds/minutes/hours), date (day of week, day of month, month and year), alarm, status and control registers. Finally, there's reset circuitry plus output buffers for both the 32kHz TCXO oscillator and the square wave output when it's enabled.

Note that since the module tracks the date as well as the time, it is more correctly described as a real-time clock and calendar (RTCC) module but we'll stick with the more common RTC term.

As well as the time and date registers, the DS3231 also provides two time-of-day alarm functions which are programmable via two sets of dedicated registers. These can generate an interrupt output signal via pin 3 ($\overline{\text{INT}}$/SQW), for feeding directly back to a micro.

When pin 3 is not being used to provide this alarm interrupt function, it can be used to provide square wave timing signals derived from the 32kHz TCXO. The square waves can be programmed for one of four frequencies: 1Hz, 1.024kHz, 4.096kHz or 8.192kHz. These are in addition to the 32.768kHz signal made available at pin 1.

All of the DS3231's function settings, along with the initial time and date, can be programmed using the I^{2}C bus to write into the appropriate internal registers. Then the time, date and status can be subsequently obtained by using the I^{2}C bus to read from the same registers.

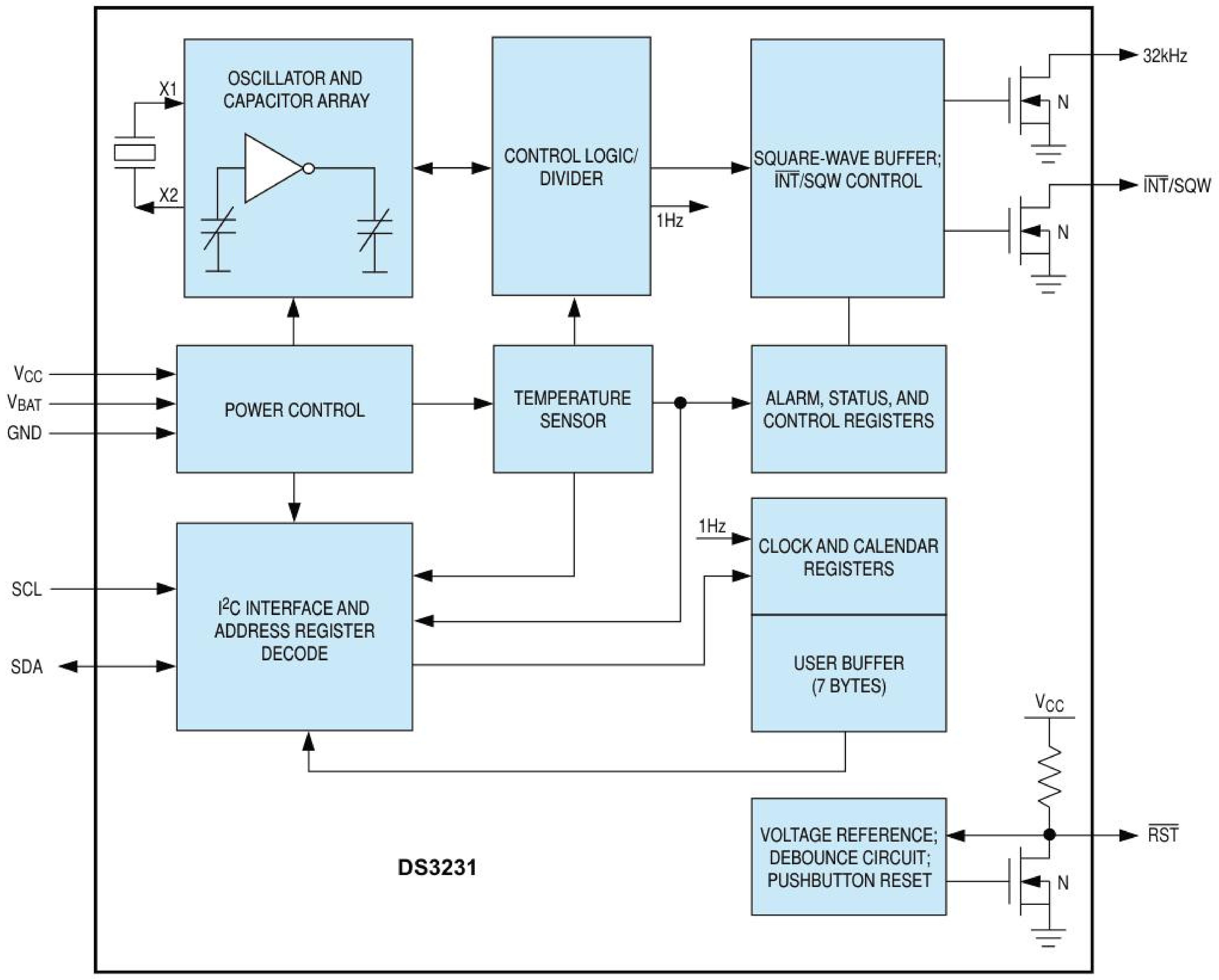
Pins 15 and 16 of the device are used for the I^{2}C bus connections: pin 15 for the SDA serial data line and pin 16 for the SCL serial clock line. On the module shown, these are both provided with surface-mount 4.7kΩ pull-up resistors to V_{CC}, as are pin 1, the 32.768kHz output and pin 3, the $\overline{\text{INT}}$/squarewave output. (The latter two pins are open-drain outputs, so they need the external pull-up resistors.)

That's probably about all you need to know about the DS3231 itself, apart from the way that pin 14 (V_{BAT}) is used for the connection to the 3.6V lithium-ion rechargeable backup battery. In the module shown here, diode D1 and its series 200Ω resistor are used to maintain the battery charge when V_{CC} is connected to the module. LED1 and its series 1kΩ resistor are used to provide a power-on indicator. We'll have more to say about battery options later.

Note the two I/O headers, labelled in Fig.1 as CON1 and CON2. CON1 provides pins for both the 32kHz and SQW/$\overline{\text{INT}}$ outputs, as well as the SCL/SDA/V_{CC}/GND bus connections, while CON2 provides only the latter four connections, essentially to allow daisy-chaining further devices to the I^{2}C bus – additional memory chips, for example.

Now let's look at IC2, the 24C32 serial EEPROM chip, which is something of a bonus. The 24C32 is a 4KB (32Kb) device, with a standard I^{2}C serial interface. In this module, the SDA line (pin 5) and SCL line (pin 6) are connected in parallel with those for IC1, to the module's SDA and SCL lines at both CON1 and CON2.

To allow IC2 to be addressed by the micro without conflicting with commands or data sent to or received from IC1, it has a different slave address on the I^{2}C bus. In fact, it can have any of eight different slave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X2
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SQUARE-WAVE BUFFER; INT/SQW CONTROL
32kHz
N
INT/SQW
N
VCC
VBAT
GND
POWER CONTROL
TEMPERATURE SENSOR
ALARM, STATUS, AND CONTROL REGISTERS
1Hz
CLOCK AND CALENDAR REGISTERS
SCL
SDA
I2C INTERFACE AND ADDRESS REGISTER DECODE
USER BUFFER (7 BYTES)
VCC
RST
VOLTAGE REFERENCE; DEBOUNCE CIRCUIT; PUSHBUTTON RESET
N
DS3231

Fig.2: block diagram for the DS3231. A comparator monitors both V_{CC} and V_{BAT} and the DS3231 is powered from whichever is higher. The oscillator is automatically temperature-compensated for accuracy.

addresses, as set by the voltage levels of pins 1, 2 and 3 (labelled A0, A1 and A2).

As shown in Fig.1, the module pulls all three pins up to V_{CC} via the 4.7kΩ resistors by default, which gives IC2 a slave address of AE/AF hex (AEh for writing, AFh for reading). But it also provides three pairs of pads on the PCB so that any of the three address pins can be pulled low (to ground) by soldering across the A0, A1 or A2 pads. This allows the slave address of IC2 to be set to any of the eight possible values, as shown.

So since the slave address of IC1 (the DS3231) is fixed at D0/1 hex (D0 for writing, D1 for reading), there is no conflict. In fact, the main reason for changing the slave address of IC2 via the wire links would be to avoid a conflict with any other devices that may be attached to the I^{2}C bus.

How it's used

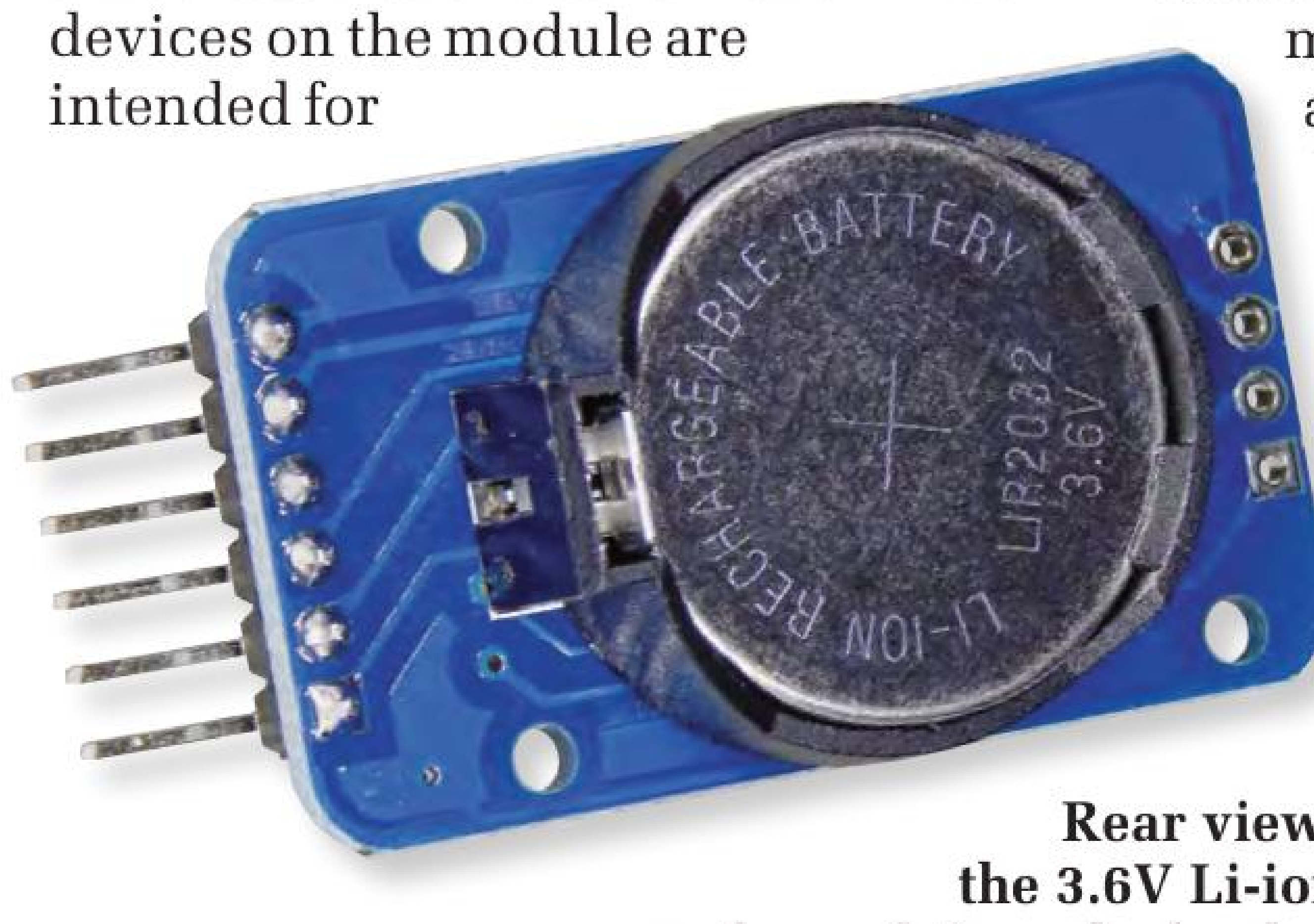
Since both the DS3231 and 24C32 devices on the module are intended for use via the I^{2}C bus, this makes it easy to use with any micro or other system provided with at least one I^{2}C interface. (Even if you don't have such an interface, you can use two GPIO pins in 'bit banging' mode, but that's outside the scope of this article.)

For example, to use it with an Arduino Uno or similar all you need to do is connect the SCL line on the module to the AD5/SCL pin on the Arduino, the SDA line to the AD4/SDA pin, the V_{CC} pin to the +5V pin and the GND pin to one of the Arduino's GND pins.

It's just as easy with the Micromite. In this case, the SCL pin connects to pin 17 on the Micromite's main I/O pin strip, while the SDA pin connects to pin 18 next to it. Then the V_{CC} and GND pins connect to the +5V pin and GND pins on the same pin strip.

Programming either of the chips on the module should also be fairly straightforward, because of the I^{2}C interfacing. The main thing to remember is that I^{2}C transactions always begin with a control byte sent by the master (the microcontroller), specifying the address of the slave device it wishes to communicate with and whether it wants to write to or read from the device.

So, for example, the control byte to initiate a write operation to one of the registers in the DS3231 would be D0h, while the control byte to read from one of the addresses in the 24C32 would be AFh (assuming it's at the default address on your module).



Rear view of the DS3231 module showing the 3.6V Li-ion backup battery (pin 14) which powers the real time clock when the supply voltage (V_{CC}) fails.

After the slave device sends back an 'ACK' or acknowledge indication (to show that it's present and ready for a transaction), the micro then sends the address of the register or memory location in the device that it wants to write data to or read it from. When this has been acknowledged, the actual write or read transactions can take place.

If this sounds a bit complicated, you'll be relieved to hear that if you're using one of the popular micros like the Arduino or Micromite, you probably don't need to worry about this yourself. That's because this has usually been taken care of in small code libraries, with functions specifically written for I^{2}C data communications. In the case of the Micromite, in fact, I^{2}C communication is handled by the MMBASIC interpreter.

For example, if you are using an Arduino, the Arduino IDE application already includes a 'Wire' library, providing about nine different functions for passing data between the micro and an I^{2}C device.

Similarly, if you're using a Micromite, you'll find that Geoff Graham's MMBASIC already includes functions like RTC SETTIME, RTC GETTIME, RTC SETREG and RTC GETREG specifically for talking to the DS1307 or DS3231 RTC devices. And there are other functions like I2C OPEN, I2C WRITE, I2C READ and I2C CLOSE for data transactions with other I^{2}C devices (like the 24C32 EEPROM chip in the current module).

Finally, there's also an automatic variable called MM.I2C, which can be read after any I^{2}C transaction to find out the result status.

So all in all, the RTC module shown with its DS3231 clock/calendar chip (and bonus 24C32 EEPROM chip) is relatively easy to use, and exceptional value for money.

Here is a link to a useful web tutorial by John Boxall of tronixlabs, explaining how to use either the DS1307 or DS3231 RTC modules with an Arduino: **http://bit.ly/2yTbIWy**

Final note: this module has onboard pull-up resistors for the I^{2}C bus, you may need to remove them, or avoid fitting pull-up resistors on the master, for it to share a bus with other peripherals.

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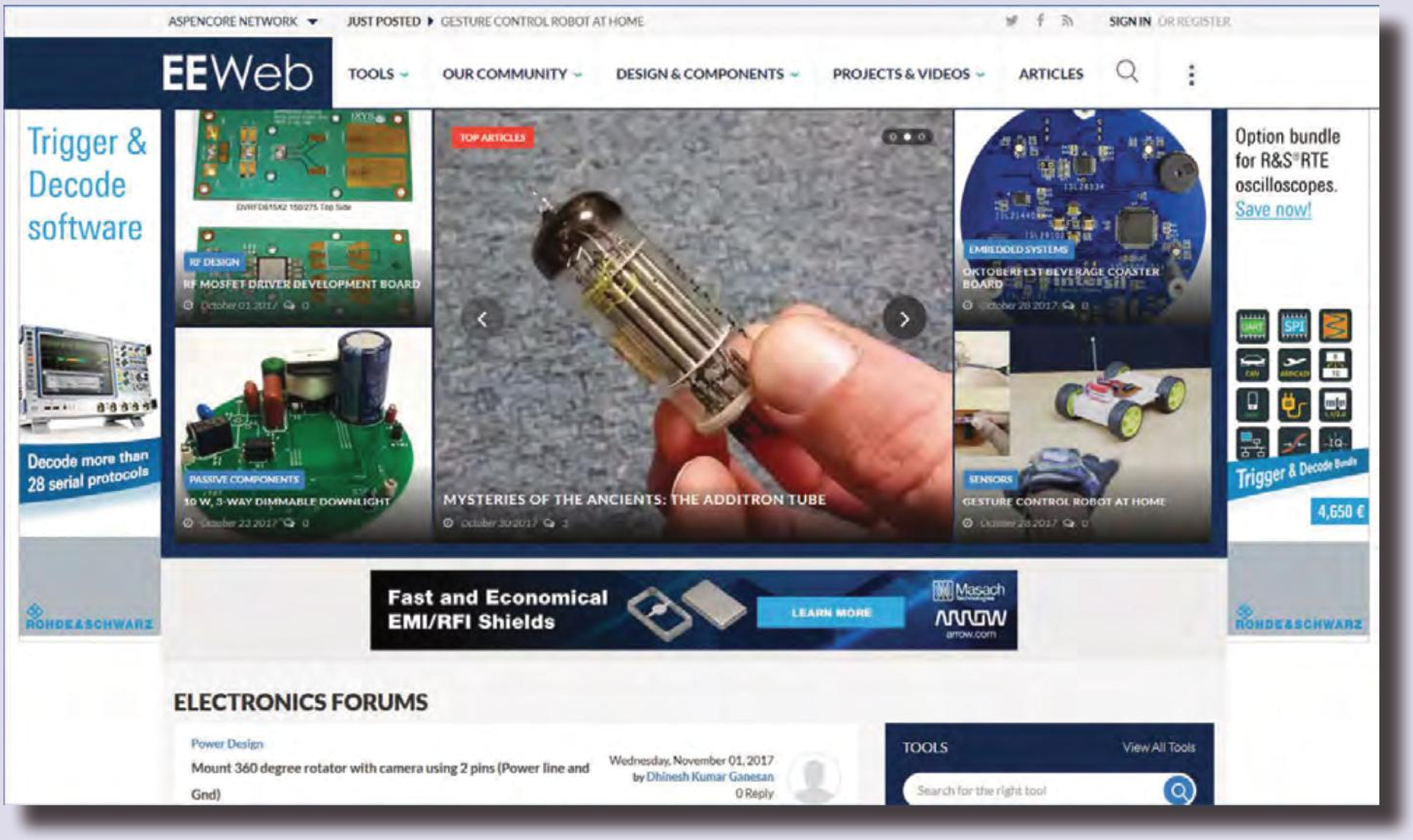
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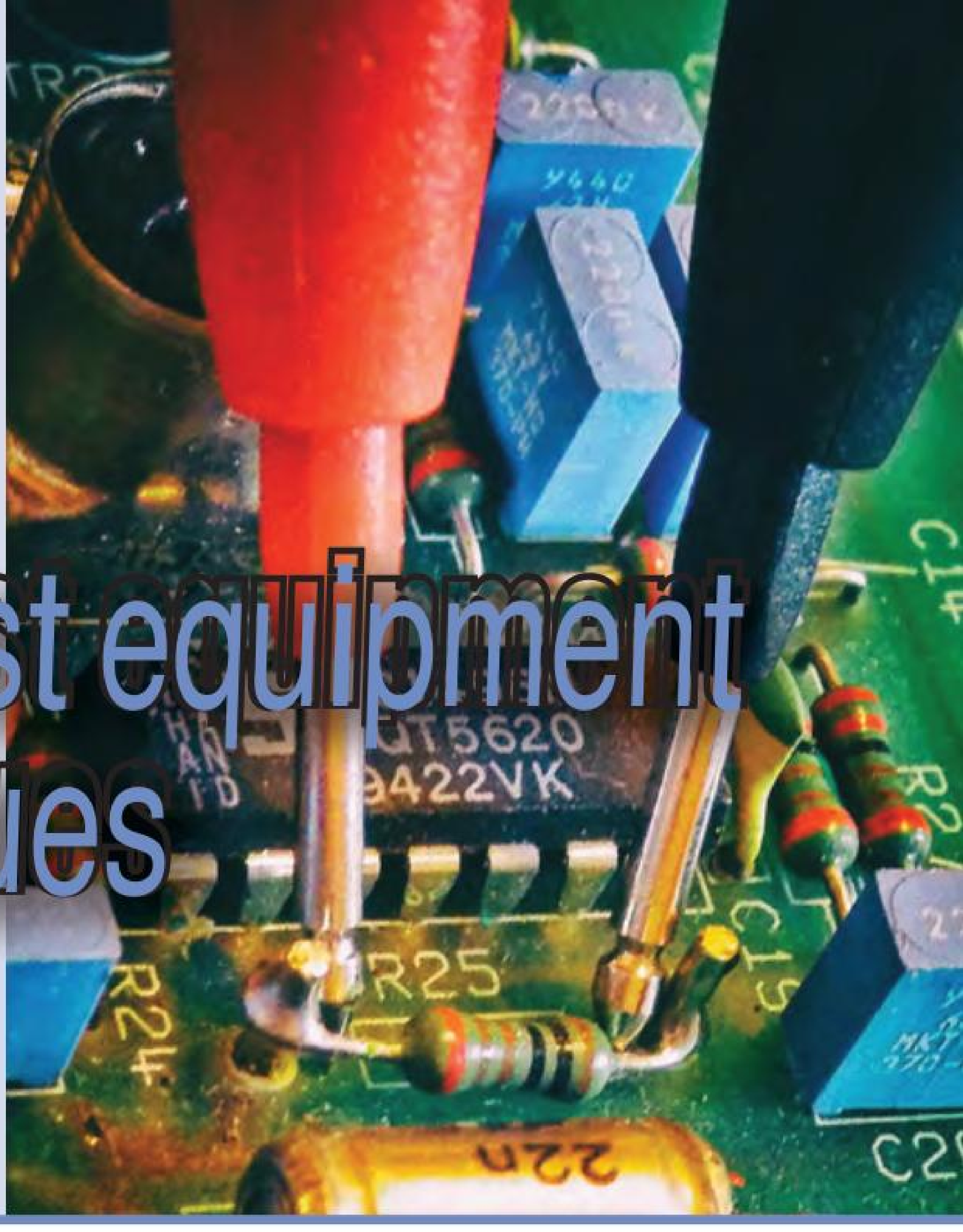
Teach-In 2018

Get testing! – electronic test equipment and measurement techniques

Part 4: Component measurement

by Mike Tooley



Welcome to *Teach-In 2018: Get testing! – electronic test equipment and measurement techniques*. This *Teach-In* series will provide you with a broad-based introduction to choosing and using a wide range of test gear, how to get the best out of each item and the pitfalls to avoid. We'll provide hints and tips on using, and – just as importantly – interpreting the results that you get. We will be dealing with familiar test gear as well as equipment designed for more specialised applications.

Our previous *Teach-In* series have dealt with specific aspects of electronics, such as PICs (*Teach-In 5*), Analogue Circuit Design (*Teach-In 6*) or popular low-cost microcontrollers (*Teach-In 7* and *8*). The current series is rather different because it has been designed to have the broadest possible appeal and is applicable to all branches of electronics. It crosses the boundaries of analogue and digital electronics with applications that span the full range of electronics – from a single-stage transistor amplifier to the most sophisticated microcontroller system. There really is something for everyone in this series!

Each part includes a simple but useful practical *Test gear project* that will build into a handy gadget that will either extend the features, ranges and usability of an existing item of test equipment or that will serve as a stand-alone instrument. We've kept the cost of these projects as low as possible and most of them can be built for less than £10 (including components, enclosure and circuit board).

This month

In this fourth part, *In theory* introduces capacitors and the parameters that we need to measure when dealing with them. *Gearing up* will examine measuring instruments and techniques used for testing common electronic components such as resistors, capacitors, inductors, diodes and junction transistors. *Get it right!* will help you avoid measurement pitfalls and provides useful tips that will help you improve the accuracy and relevance of your measurements. Finally, our fourth *Test Gear Project* is a constant-current junction tester that will help you verify the function and pin connection of common types of diode and bipolar transistor.

In theory: Capacitor measurements

A capacitor is a device for storing electric charge and consists of two parallel conductive plates separated by an insulating dielectric material. When a voltage is applied across the plates, the electric field in the dielectric displaces electric charges, and thereby stores energy. It is assumed that there are no free charges in the dielectric (at least in the ideal case), and that while they are displaced, they are not free to move around (as in a conductor). A capacitor is specified with various parameters, including the value of its capacitance, tolerance, working voltage and construction method, which is usually one of the following categories:

- Plastic film
- Ceramic
- Electrolytic
- Other types (eg, mica and air-spaced).

Each main type has its own distinct electrical and physical characteristics and these often have an impact on the tests and measurements carried out when determining whether or not a capacitor is functional and fit for purpose. Note that we are not just concerned with the value of capacitance, as there may be other important factors present that can have a significant impact on the way in which a circuit will operate, so we will begin by examining some of their important characteristics and properties.

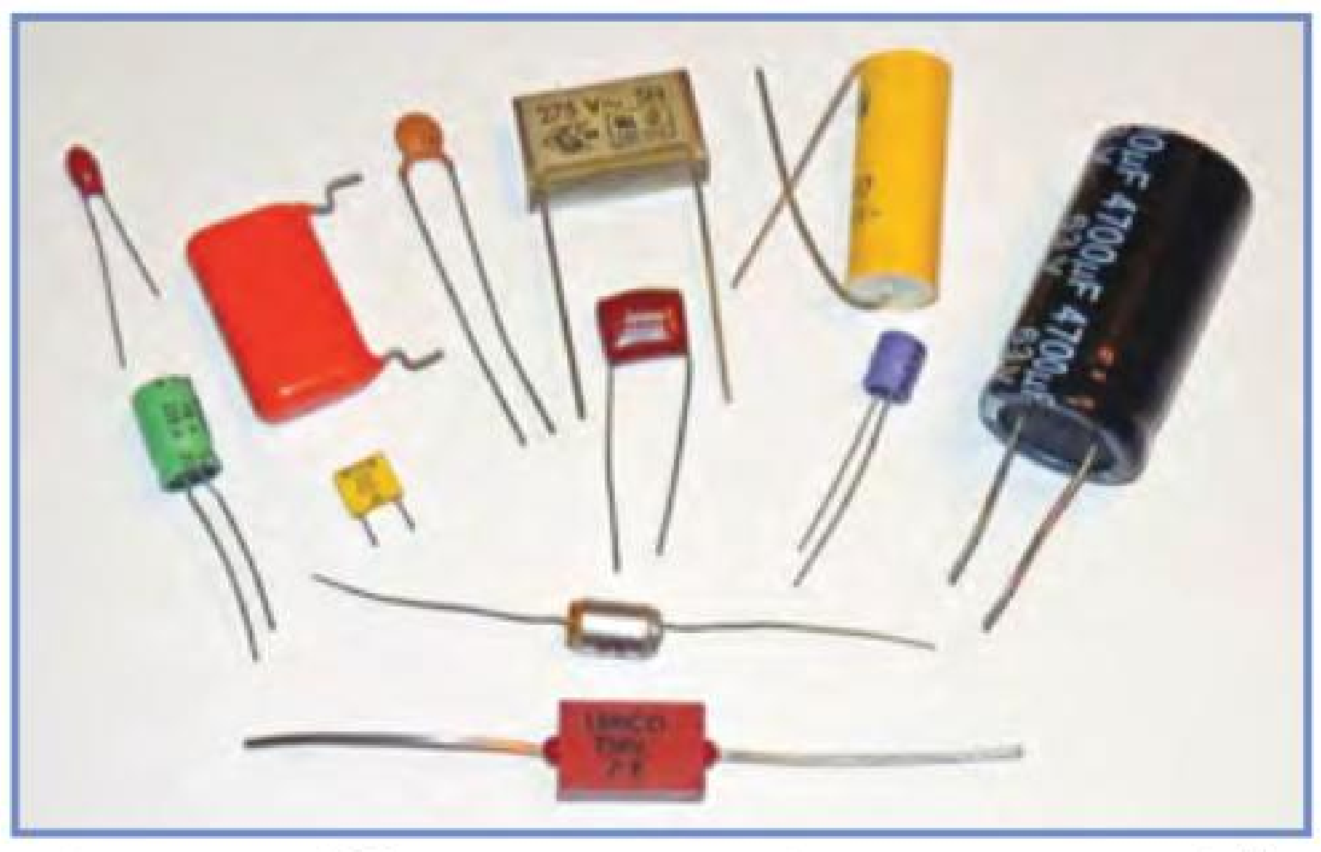


Fig.4.1 Different capacitor types, with values ranging from 12pF to 4,700μF

Film capacitors

The electrodes of metalised film capacitors consist of an extremely

Table 4.1 Properties of various types of film capacitor

Type of capacitor	Typical range of values	Typical tolerance	Typical working voltage	Temperature range	Typical temperature coefficient	Typical insulation resistance
Miniature polypropylene	100pF to 10nF	±10%	100V	–55°C to +85°C	–200ppm / °C	$> 10^9\Omega$
Miniature polyester	1nF to 1μF	±10%	50V to 100V	–55°C to +100°C	+330ppm / °C	$> 5\times10^8\Omega$
Metallised polyester	10nF to 470nF	±10%	100V to 400V	–40°C to +85°C	+200ppm / °C	$> 5\times10^8\Omega$
Metallised polypropylene	10nF to 1μF	±20%	275V AC	–55°C to +100°C	–200ppm / °C	$> 5\times10^7\Omega$

Table 4.2 Properties of various types of ceramic capacitor

Type of capacitor	Typical range of values	Typical tolerance	Typical working voltage	Temperature range	Typical temp coefficient	Typical insulation resistance
Miniature low-K ceramic plate	1.8pF to 470pF	±2%	100V	–55°C to +85°C	–750ppm / °C	> 100kΩ
Miniature high-K ceramic plate	1nF to 47nF	-20%	100V	–55°C to +85°C	–60% to +15%	> 10MΩ
General purpose ceramic disc	1pF to 100nF	±10%	50V	–25°C to +80°C	±10%	> 10MΩ
SMD ceramic chip	10pF to 100nF	±5%	50V	–55°C to +125°C	±15%	> 100kΩ

thin layer of metal separated by an *insulating* film dielectric. The polymer dielectric film is based on a material such as polyester, polycarbonate, teflon, polypropylene, or polystyrene. Film capacitors are available in two broad categories: film-foil, and metallised film. Film-foil capacitors are made of alternating layers of plastic film and metal foil, while metallised film capacitors have the metal layer vacuum deposited directly on to the film. In general, film-foil is better at handling high current, while metallised film capacitors are much better at self-healing.

Film capacitors offer stable electrical properties with a reasonable trade-off between performance and cost. Film capacitors normally exhibit low leakage and little variation with age. When measuring such components, the main parameters of interest include the variation of capacitance with temperature, the dissipation factor (DF), and dielectric absorption (DA).

The main drawback of film capacitors is their relatively low dielectric constant (K) but this is partly compensated for by their relatively high breakdown voltage. K values vary from a low of about 2.2 for teflon to about 8 for materials with better dielectric properties. Unfortunately, the rule-of-thumb is that the higher the K (and therefore the smaller the size), the worse the electrical properties tend to be. Likewise, film capacitors have not made an entirely graceful transition into the age of surface-mount devices and, while some film dielectrics are suitable for surface mounting, most have problems withstanding the heat of soldering. As a result, capacitor manufacturers have responded by developing several new dielectrics. The properties of various common types of film capacitor are summarised in Table 4.1.

Ceramic capacitors

Ceramic capacitors are suitable for most non-critical applications and they are available in a wide range of values and working voltages. Ceramic capacitors have high-K values and, by virtue of their inherent heat resistance are eminently suitable for flow soldering and surface mounting. Ceramic capacitors also offer low values of effective series resistance (ESR) and this makes them eminently suitable for use in high-speed switching and RF applications.

Low-K ceramic capacitors usually exhibit relatively low breakdown voltage (often as little as 50V) and values may be limited to 1nF, or less. High-K ceramic capacitors have relatively poor electrical properties and their values can be very dependent on temperature, voltage, and frequency, coupled with a significant aging rate. Unlike many other capacitors, ceramic components have no self-healing mechanism. As a result, manufacturers need to maintain a high level of quality control over the dielectric material. The properties of various common types of ceramic capacitor are summarised in Table 4.2.

Electrolytic capacitors

As the name implies, electrolytic capacitors use a conductive layer (ie, an electrolyte) between the two metal plates. Early electrolytic capacitors were 'wet' and used a conductive salt in a solvent solution, but modern components make use of an oxide film that's grown on the anode (positive plate) using an electrochemical process. The films are very thin and have relatively high-K values, resulting in a large value of capacitance in a small package.

Because of their large capacity, electrolytic capacitors are often used in power supplies. Unfortunately, electrolytic components suffer from several problems, including leakage (see later), relatively poor service life, appreciable equivalent series resistance (ESR), appreciable series inductance (ESL), poor low-temperature performance, and a service life that is significantly reduced when operating at relatively high ambient temperatures. In addition, there's a need to apply a polarising voltage of the correct polarity. The properties of various common types of electrolytic capacitor are summarised in Table 4.3.

Reverse voltage

Normally, a modest value of reverse voltage (up to 1.5V) is considered to be acceptable for most types of aluminium electrolytic capacitor. Application of a higher reverse voltage for a long time may result in deterioration of the capacitor (a reduction in capacitance together with an increase in leakage current). While the momentary application of a reverse voltage will not normally result in failure of an electrolytic capacitor, if a reverse potential is present for an appreciable period there is a danger that internal pressure will build due to the power dissipated in the dielectric. In many cases this will simply cause the pressure seals to rupture. However, if the applied

Table 4.3 Properties of various types of electrolytic capacitor

Type of capacitor	Typical range of values	Typical working voltage	Temp range	Typical ripple current	Typical leakage current	Typical ESR	Life expectancy
Miniature solid aluminium radial lead electrolytic	1µF to 2,200µF	6.3V to 25V	–55°C to +105°C	0.4A to 9.7A	0.01CV or 4µA	15Ω to 350Ω	2,000 hours at 105°C
Miniature SMD electrolytic	1µF to 1,000µF	6.3V to 50V	–45°C to +85°C	0.01A to 0.33A	0.01CV or 3µA	0.4Ω to 166Ω	2,000 hours at 85°C
SMD low-ESR electrolytic	100µF to 1,000µF	6.3V to 50V	–55°C to +105°C	0.3A to 0.45A	0.01CV or 3µA	0.17Ω to 0.4Ω	2,000 hours at 85°C
Low-ESR radial lead electrolytic	2.2µF to 1,000µF	16V to 100V	–55°C to +105°C	0.03A to 1.5A	0.01CV or 2µA	0.04Ω to 2.8Ω	5,000 hours at 85°C
PCB-mounting electrolytic	220µF to 22,000µF	16V to 400V	–40°C to +85°C	0.7A to 4.1A	0.02CV	0.03Ω to 4Ω	2,000 hours at 85°C
Large power supply electrolytic	1,000µF to 47,000µF	25V to 385V	–40°C to +85°C	10A to 42A	0.006CV or 4µA	0.005Ω to 0.07Ω	4,000 hours at 85°C

potential is large there will be appreciable heat dissipation within the component and, as a result, it may explode!

Other types

Other types of capacitor use dielectrics such as air, glass, mica, and porcelain. Capacitors that use these dielectrics tend to be used in specialised applications such as high-voltage and/or high-frequency circuits. In addition, dielectrics such as silicon dioxide and sapphire are used for microwave applications. The electrical properties of these capacitors are quite diverse, but those designed for microwave and SMT (surface-mounting technology) tend to have electrical properties that are similar to plastic film types. The range of capacitance values tends to be restricted from about 1pF (for small mica, glass and porcelain types) to about 100nF for larger SMT types.

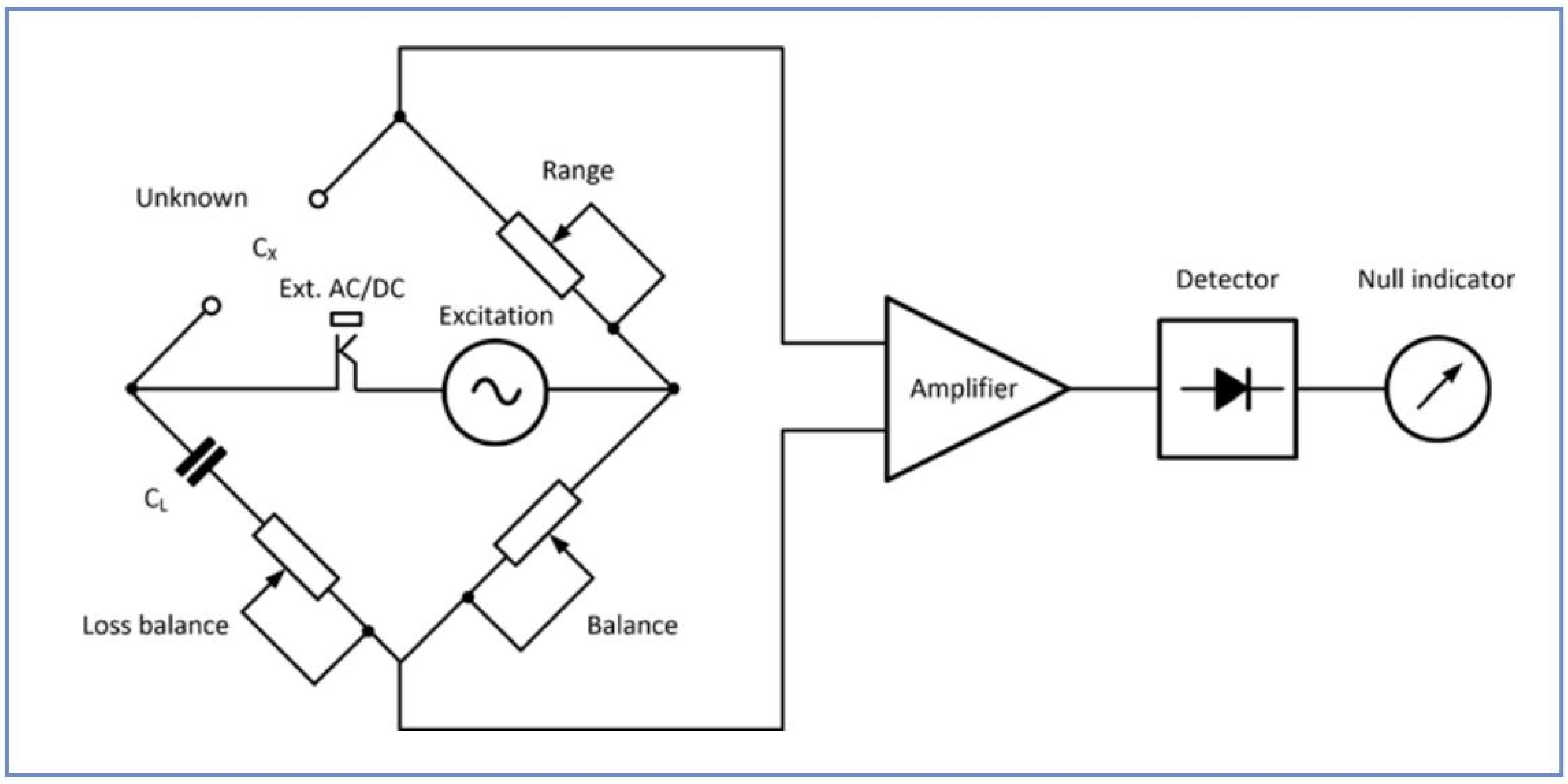

Unknown
Cx
Range
Ext. AC/DC
Excitation
CL
Loss balance
Balance
Amplifier
Detector
Null indicator

Fig.4.3 Simplified arrangement of an AC bridge

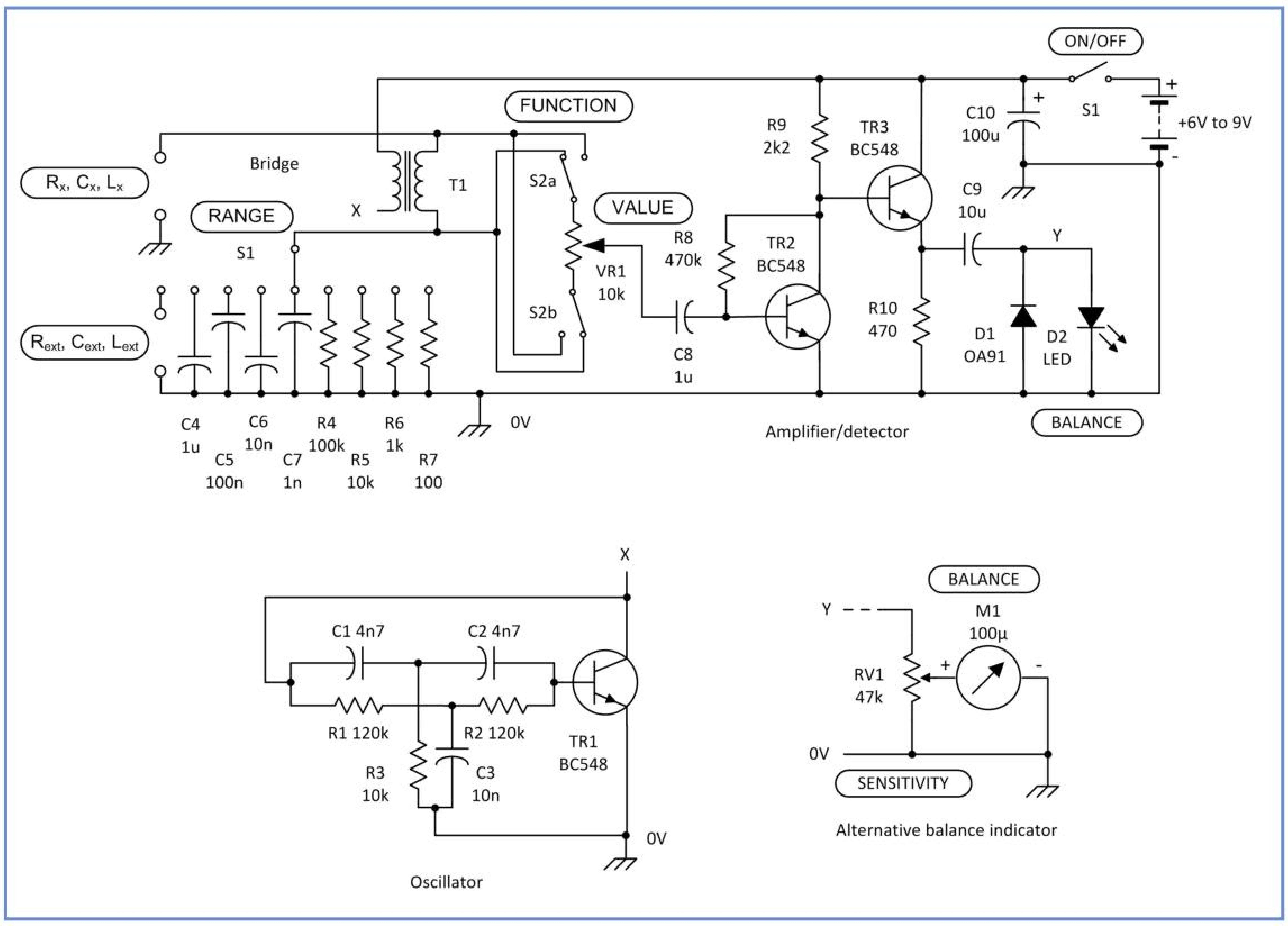

ON/OFF
FUNCTION
Bridge
Rx, Cx, Lx
RANGE
S1
T1
X
S2a
VALUE
S2b
VR1
10k
R8
470k
TR2
BC548
R9
2k2
TR3
BC548
C10
100u
S1
+6V to 9V
C9
10u
Y
C8
1u
R10
470
D1
OA91
D2
LED
Rext, Cext, Lext
C4
1u
C5
100n
C6
10n
C7
1n
R4
100k
R5
10k
R6
1k
R7
100
0V
Amplifier/detector
BALANCE
X
C1 4n7
C2 4n7
R1 120k
R2 120k
R3
10k
C3
10n
TR1
BC548
0V
Oscillator
BALANCE
Y
M1
100µ
RV1
47k
0V
SENSITIVITY
Alternative balance indicator

Fig.4.4 A simple AC bridge suitable for home construction (the bridge is calibrated using known components)

Equivalent circuit of a capacitor

The equivalent circuit of a capacitor is shows in Fig. 4.2. The components shown are:

- Effective capacitance, C
- Parallel (or 'shunt') resistance, R_P – through which a leakage current flows
- Effective series resistance (ESR), R_S
- Effective series inductance (ESL), L_S.

It is important to realise that the components shown in Fig.4.2 have quite different effects on the capacitor's performance in a working circuit. For example, whereas L_S is insignificant at low frequencies, it does become increasingly important at very high frequencies. R_P, on the other hand is of little consequence in low-impedance equipment (such as power supplies) but it does become important in high-impedance circuit applications (for example, in a sample-and-hold circuit). Conversely, while R_S is unimportant in high-impedance circuits, it becomes critical in low-impedance situations (such as power supplies, amplifiers and switching circuits).

While a very small amount of power is dissipated in R_P, a very significant power is dissipated in R_S when appreciable ripple (or other AC) current is flowing through the component. The power loss in R_S results in internal heating. In some cases, this can be responsible for the premature failure of the component. Nowadays, the very wide use of high-current switch-mode power supplies has increased the demand for low-impedance capacitors with high ripple current ratings. These must always have a low value of R_S.

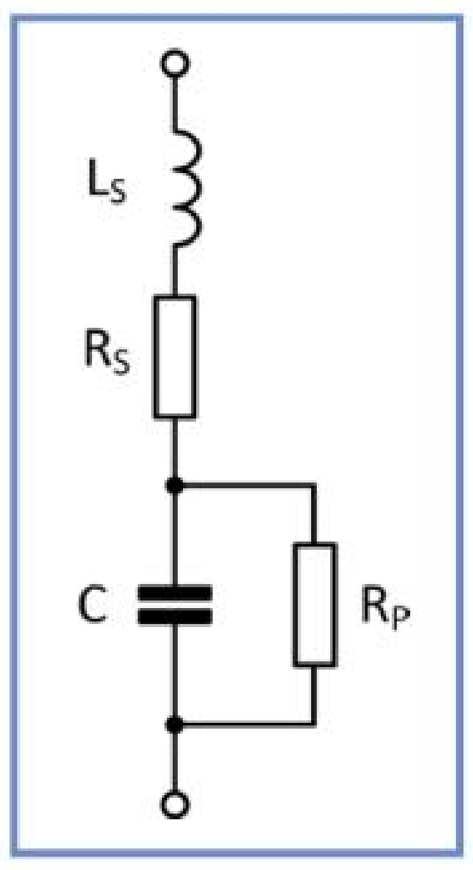


Fig.4.2 Equivalent circuit of a capacitor

Measuring capacitance

The capacitance (C) can be measured in various ways. The traditional method is by using an AC bridge arrangement, like that shown in Fig. 4.3. The bridge is adjusted for a null indication and in this condition, is said to be 'balanced'. In the balanced condition the value of resistance is read and interpolated from a calibrated scale. Note that it is possible to inject DC bias or make use of external AC excitation in Fig. 4.3. Modern bridges can be automated and use more sophisticated techniques to achieve balance over a very wide range of capacitance, inductance and resistance (as we shall see later). A simple bridge circuit, suitable for home construction, is shown in Fig.4.4.

Effective series resistance (ESR)

ESR is the internal resistance of the capacitor expressed as a single resistance value connected in series with a perfect capacitor (see Fig. 4.2). It is important to note that ESR is made up of the sum of the resistance loss in the dielectric *and* the conducting path between the capacitor plates and the external connections. ESR varies slightly with frequency, usually falling to a minimum value in the range

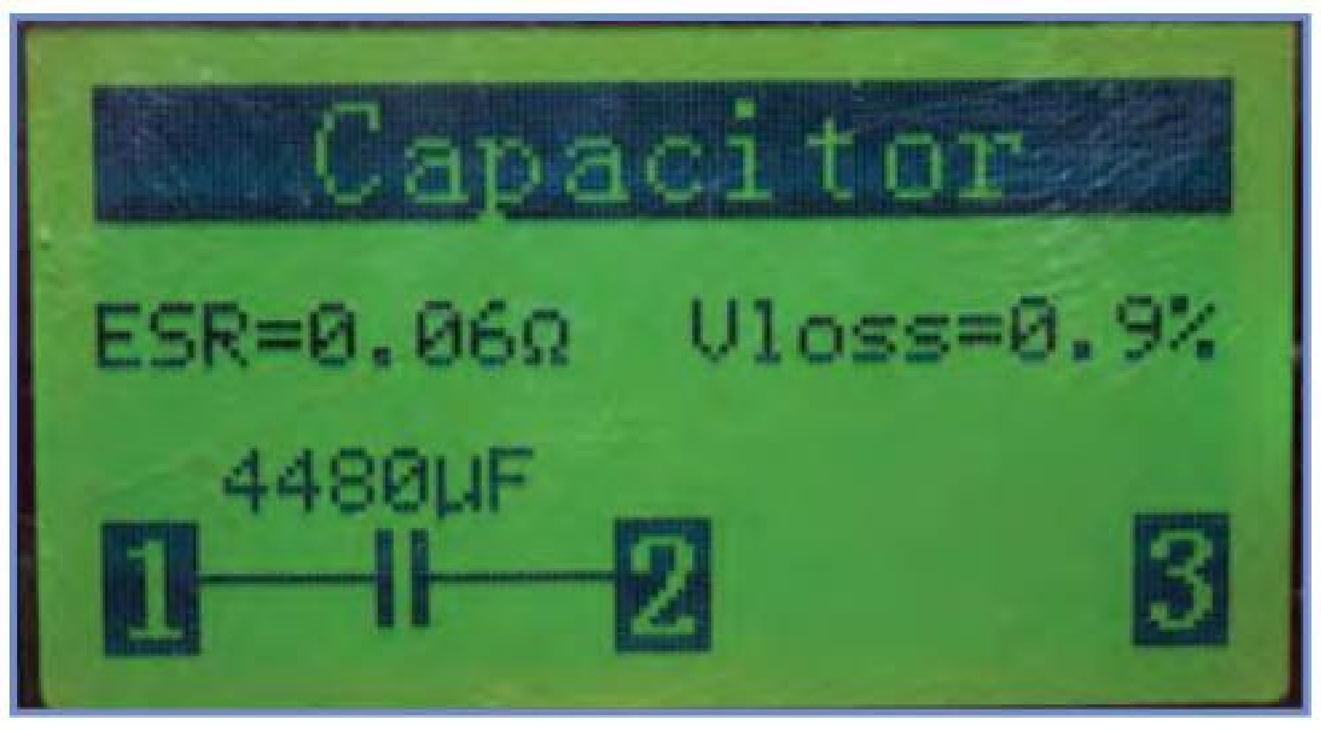

Capacitor
ESR=0.06Ω Vloss=0.9%
4480µF
1
2
3

Fig.4.5 Using a low-cost component tester to check capacitance (4480µF), ESR (0.06Ω), and voltage loss (0.9%)

Table 4.4 Typical values of *D* and ESR for differently rated electrolytic capacitors

Capacitor type	Rated working voltage (V)	Dissipation factor (D)	ESR (Ω)	Maximum ripple current (mA)
Conventional electrolytic	16	0.16	0.97	320
	35	0.12	0.72	480
	63	0.10	0.60	580
Low-ESR electrolytic	16	0.10	0.40	450
	35	0.07	0.28	700
	63	0.05	0.21	1100

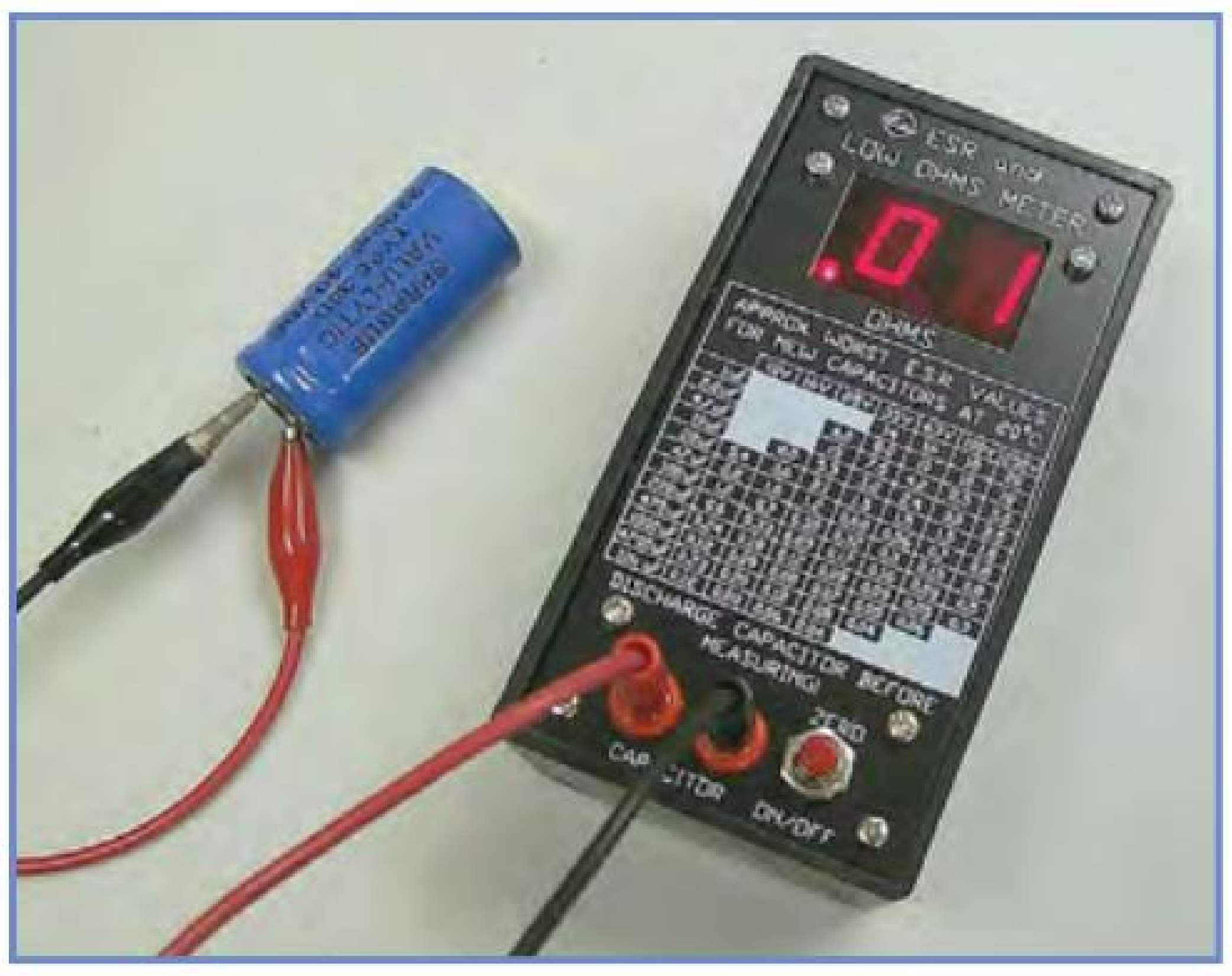


Fig.4.6 Measuring ESR using a dedicated ESR meter. The measured value is checked against the table of 'worst case' ESR values shown on the instrument's front panel

50kHz to 100kHz. Note also that the power loss in a capacitor increases with ESR. A low value of ESR is essential in many applications and is often the reason why an apparently 'good' component fails to work effectively.

Voltage loss (V_{loss})

When a charged capacitor is suddenly discharged there is an initial voltage drop resulting from its ESR at the moment of discharge. This voltage drop is usually expressed as a percentage of the applied test voltage. For large value components V_{loss} is often less than 1%, but larger values (associated with higher values of ESR) can be indicative of a defective component.

Dissipation Factor (D or DF)

The dissipation factor of a capacitor is the ratio of the effective series resistance (ESR) of the component to its reactance (X_C) at a specified frequency. Dissipation factor is sometimes also referred to as 'tan δ' – ie, the tangent of the 'loss angle' of the capacitor in which ESR (R_S) and reactance (X_C) are the (perpendicular) adjacent and opposite sides in an impedance triangle, see Fig. 4.7.

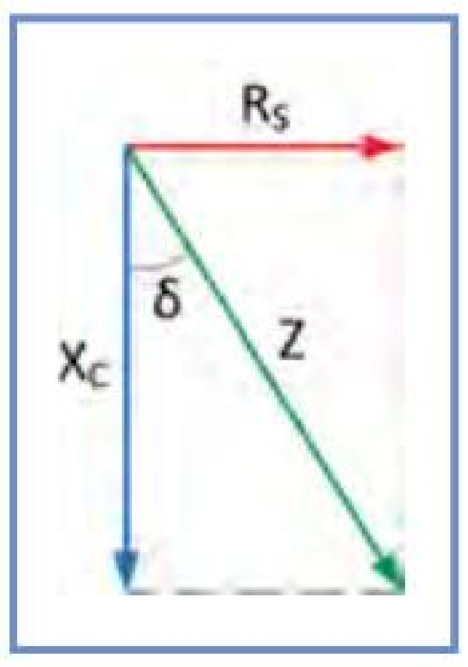


Fig.4.7 Relationship between reactance (X_C), ESR (R_S), and dissipation factor (D)in a capacitor's impedance triangle.

Since reactance (X_C) varies with frequency, a capacitor's dissipation factor will also vary with frequency (as will its ESR). Dissipation factor is usually quoted for sinusoidal AC power applications and is less meaningful when conditions are non-sinusoidal (as in switched-mode power supplies and Class-C and D power amplifiers). Dissipation factor is given by:

$$D = \tan\delta = \frac{R_S}{X_C} = \frac{R_S}{\left(\frac{1}{2\pi fC}\right)} = 2\pi fCR_S$$

To help put this into context, consider the following example. A capacitor of 68µF with an ESR of 1.5Ω is used at a frequency of 50Hz. The dissipation factor is given by:

$$D = 2\pi fCR_S = 6.28\times50\times68\times10^{-6}\times1.5 = 0.032$$

(or 3.2%) Table 4.4 lists typical electrolytic capacitor characteristics in relation to common voltage ratings.

Quality factor (Q or QF)

Q is the ratio of capacitive reactance (X_C) to ESR at a specified frequency. Quality factor is the inverse of the dissipation factor:

$$Q = \frac{1}{D} \quad \text{and} \quad D = \frac{1}{Q}$$

Most 'universal' bridges (see page 42) will allow you to measure *Q* and *D* to reasonable accuracy.

Dielectric absorption (DA)

Few electronic enthusiasts can fail to have noticed that, once charged, a capacitor seems to retain some of its charge after a concerted attempt to discharge it. Even shorting its terminals for several seconds can stubbornly fail to remove the charge from a large value capacitor. The reason for this puzzling phenomenon is dielectric absorption (sometimes referred to as 'voltage retention' or 'soakage'). DA can be a source of error in sample-and-hold circuits and precision integrators and can also be a problem in high-voltage applications.

Dielectric absorption can be tested by the following procedure:

1. Charge the capacitor to its rated voltage (eg, 63V, 100V or 150V) for five minutes
2. Disconnect the capacitor from its charging supply
3. Short the capacitor terminals for five seconds, then leave the capacitor to recover for 60 seconds
4. Connect a high-impedance voltmeter to the capacitor terminals and measure the voltage present.

The value of DA is then given by:

$$DA = \frac{V_R}{V_S}\times100\%$$

where V_R is the recovery voltage and V_S is the charging supply voltage. For example, if a capacitor is charged from a 63V supply (its rated working voltage) and it exhibits a recovery voltage of 9V the value of dielectric absorption will be given by:

$$DA = \frac{7}{63}\times100\% = \frac{1}{9}\times100\%$$
$$= 0.11\times100\% = 11\%$$

Equivalent series inductance (ESL)

Equivalent series inductance (ESL) is the effective inductance of the capacitor, including its connecting leads, tags or pins (see Fig.4.2). It's important to be aware that ESL is made up of the sum of the component's internal inductance and the inductance of the conducting path between the capacitor plates and its external connections. ESL can greatly reduce the effectiveness of a capacitor at high frequencies. It is also responsible for a sharp dip in impedance that occurs at the series resonant frequency of some types of capacitor. Depending on the component type and value, this resonant effect occurs at frequencies of between about 700kHz for a small axial lead electrolytic to around 40MHz for small PCB-mounting film dielectric capacitors. Typical values of ESL range from about 20nH for PCB-mounting parts to 60nH for wire-ended components.

Insulation resistance (IR)

Insulation or leakage resistance is the parallel (or 'shunt') resistance of a capacitor. Insulation resistance is usually specified in MΩ (a typical value for an electrolytic capacitor being in the range 1MΩ to 10MΩ (the lower values

Fig.4.8 Measuring the insulation resistance of a capacitor with a multimeter is usually unsuccessful and invariably produces a meaningless over-range indication

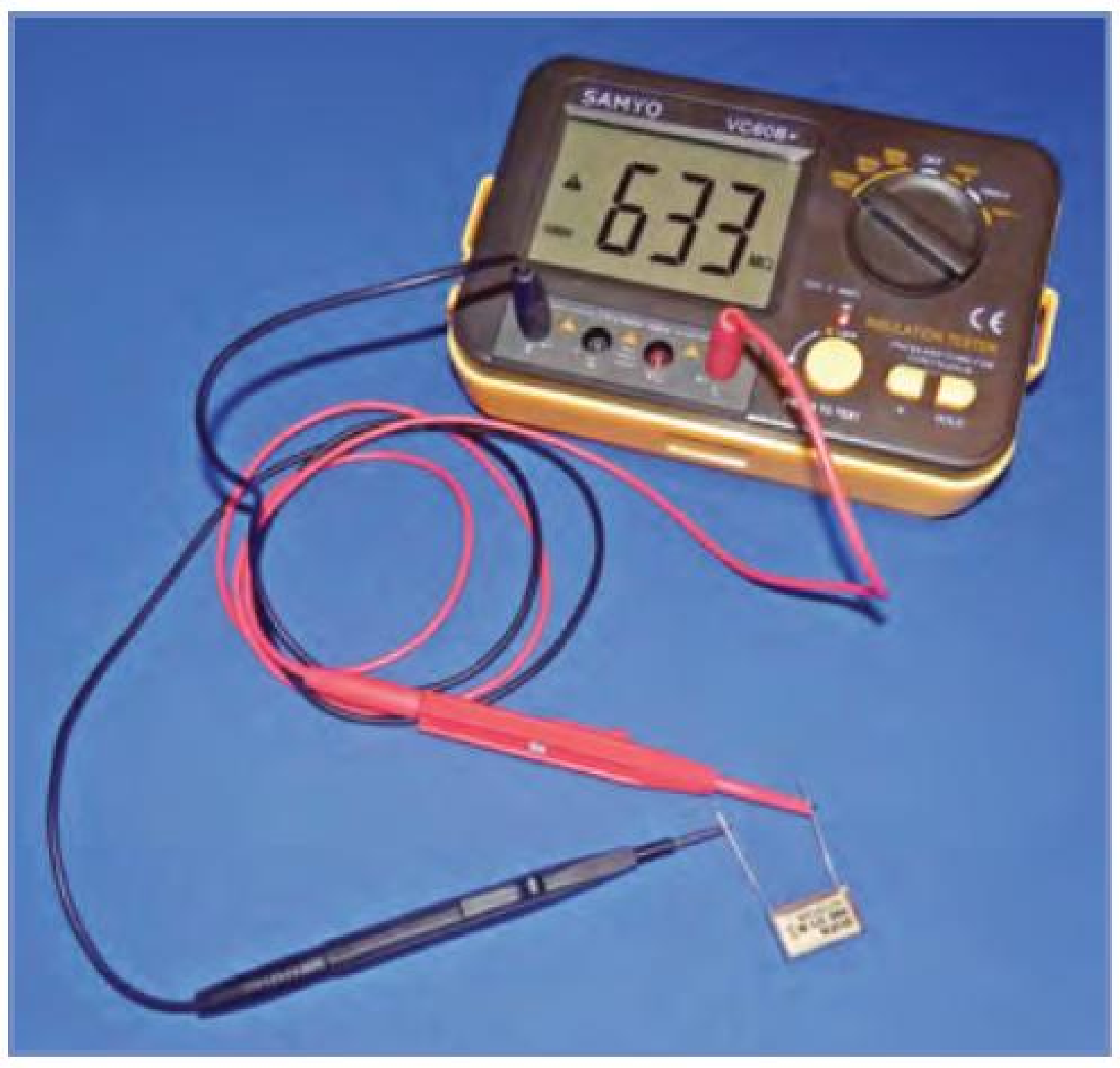


Fig.4.9 Using an insulation tester to check a Class X2 capacitor at an applied voltage of 1kV (well beyond the component's normal rating). After 60s of testing, the indicated value of IR is 633MΩ

of insulation resistance being associated with higher values of capacitance). Some manufacturers quote insulation resistance as a product of the insulation resistance (in MΩ) and capacitance (in μF). The insulation resistance may thus be specified in MΩ-μF. To determine the insulation resistance for a given capacitor it is simply a matter of dividing the MΩ-μF value by the component's capacitance. For example, if a 2.2μF capacitor is taken from a range with a quoted IR value of 4.4MΩ-μF, it will have an insulation resistance of 2MΩ. Note that insulation resistance varies with applied voltage and tests should normally be carried out at, or close to, a component's rated working voltage.

Insulation resistance is mainly a concern with large (as well as some not-so-large) electrolytic capacitors, but it can also be of concern for film capacitors in some analogue applications (such as integrators and sample-and-hold circuits). For film capacitors, the lower the dielectric constant, the higher the insulation resistance tends to be.

Leakage current

Leakage current is often specified in terms of the amount of stored charge (ie, as a constant multiple of capacitance (*C*) and applied voltage (*V*) – typically 0.01*CV*) or as a maximum current in μA (whichever is the greater). Leakage current is dependent on insulation resistance and the higher this is the lower will be the leakage current. Typical leakage currents for electrolytic capacitors are in the range 1 to 5μA. Leakage current is determined by the following factors:

- Applied voltage
- Temperature
- Capacitance value.

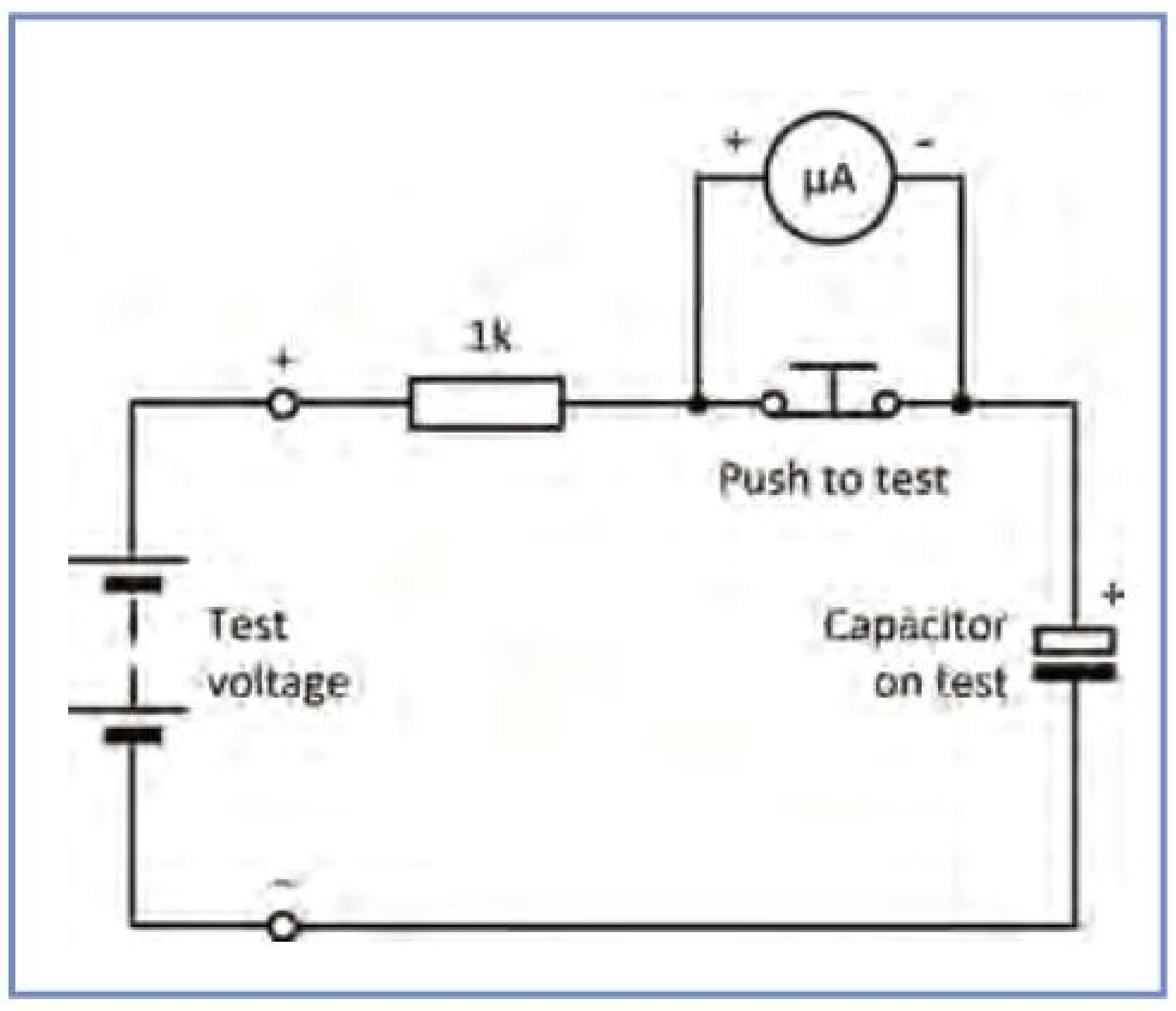


Fig.4.10 Method for measuring capacitor leakage current. Note that the capacitor must be fully charged to its working voltage before operating the test button. The series resistor (R) is used to limit the inrush current during initial charging

Leakage current can be measured using an arrangement like that shown in Fig. 4.10. Note that attempting to measure leakage *resistance* using an ordinary multimeter is rarely successful – as discussed earlier!

Gearing up: Component testing

Fortunately, there's a wide choice of test equipment suitable for measuring different types of component including:

- Multimeters with built-in component testing facilities
- Dedicated component testers for different component types
- AC and DC 'universal' bridges (both manual and automatic types).

The multimeters that we introduced in *Part 1* of *Teach-In 2018* usually incorporate basic facilities for testing components, including resistors, capacitors, diodes and transistors. In many cases this might be all that you need to check the value of resistors and capacitors with reasonable accuracy. However, in some cases, you might require additional information or need to work to a high degree of accuracy. For example, when used on the capacitance ranges most digital multimeters will work to an accuracy of about 2.5% but in some applications, you might need to work to a closer tolerance than this. In addition, you might need to know how lossy the component is and whether, or not, it is suitable for use in a critical application where the presence of leakage current might affect working conditions.

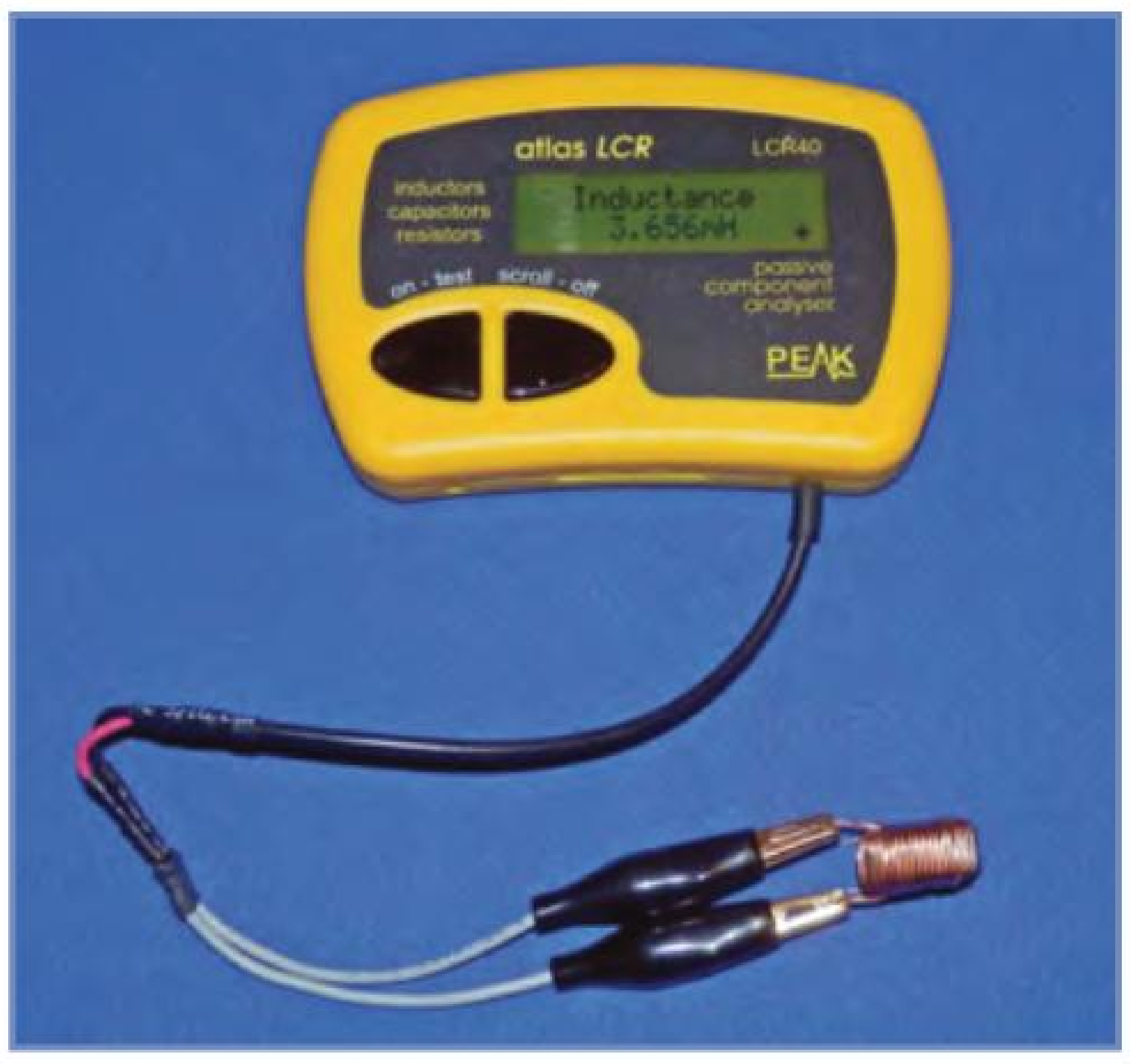


Fig.4.11 The Atlas LCR40 component tester being used to test a small toroidal inductor. The display is scrolled for additional information

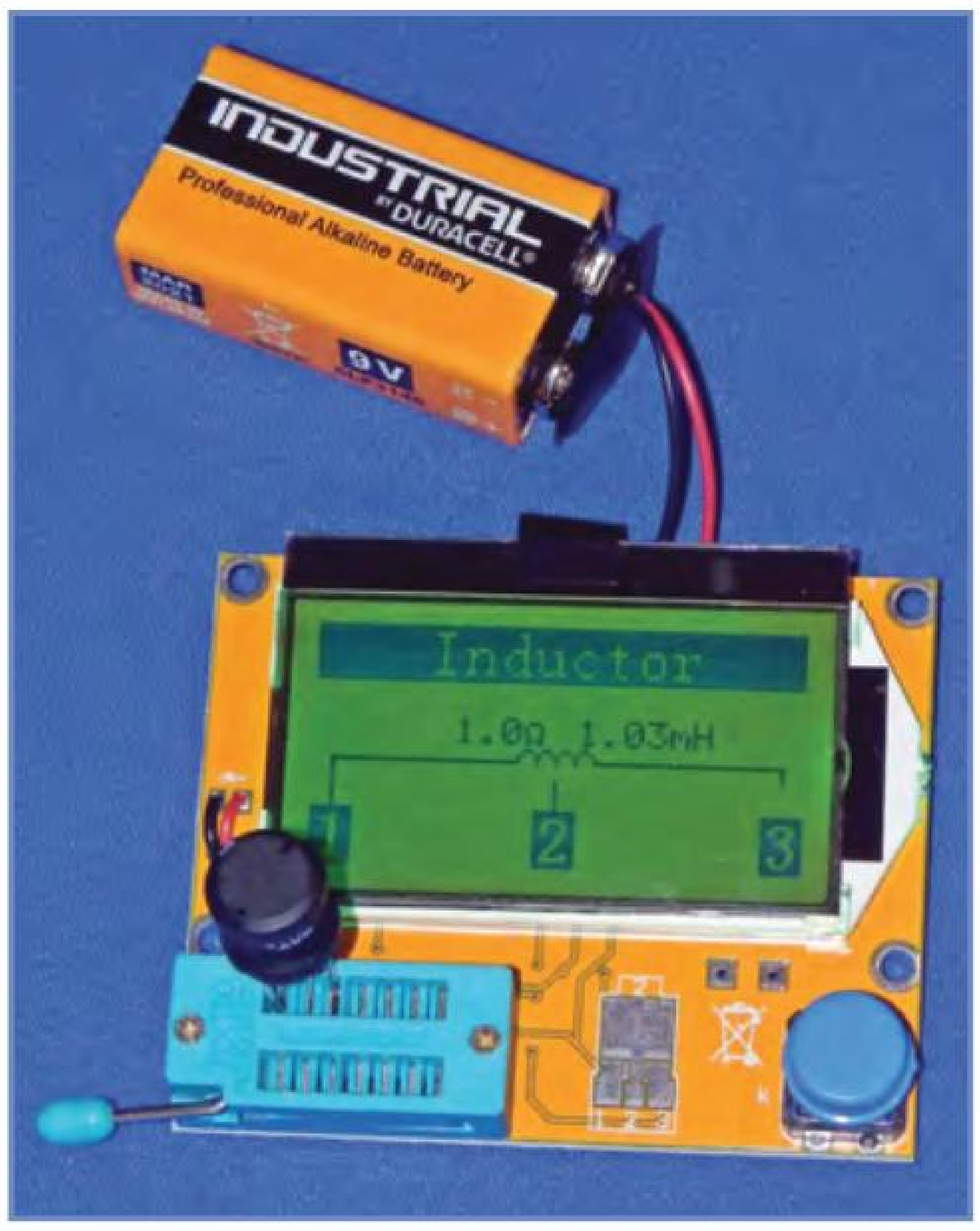


Fig.4.12 A low-cost imported component tester being used to measure a 1mH ferrite-cored inductor. The display shows inductance (1.03mH) and ESR (1.0Ω)

If you need to measure components on a regular basis it might be well worth investing in a dedicated component tester. These are available from a variety of sources at costs ranging from well under £100 for a basic instrument to several hundred pounds for a sophisticated tester that offers an accuracy of 1% or better coupled with a wide measurement range. The Peak Electronics LCR40 (see Fig. 4.11) is an excellent example of a small hand-held component tester that greatly simplifies the testing of inductors, capacitors and resistors. The LCR40 does everything automatically and identifies the component type as well as measuring and displaying its data. An important feature of this instrument is that it automatically selects the best signal level and frequency for the component under test. The Peak Electronics LCR45 is similar to the LCR40 but also measures and displays complex impedance, complex admittance (both displayed in rectangular form) as well as the magnitude and phase of impedance displayed in polar form.

An alternative (and somewhat more traditional) solution to the problem of measuring inductance, capacitance, and resistance is that of using a 'universal' LCR bridge. These are regularly available on the second-hand market and also from on-line auction sites at bargain prices. For example, the Marconi TF2700 LCR bridge (shown in Fig.4.13) is capable of measuring values from 0.5μF to 1100μF on the capacitance ranges, 0.2μH to 110H on the inductance ranges, and 0.01Ω to 11MΩ on the resistance ranges. In addition, the instrument can be used to measure D and Q at a frequency of 1kHz. It should go without saying that this instrument requires manual operation and interpolation of scale readings, so is not as easy to use as an automatic component tester!

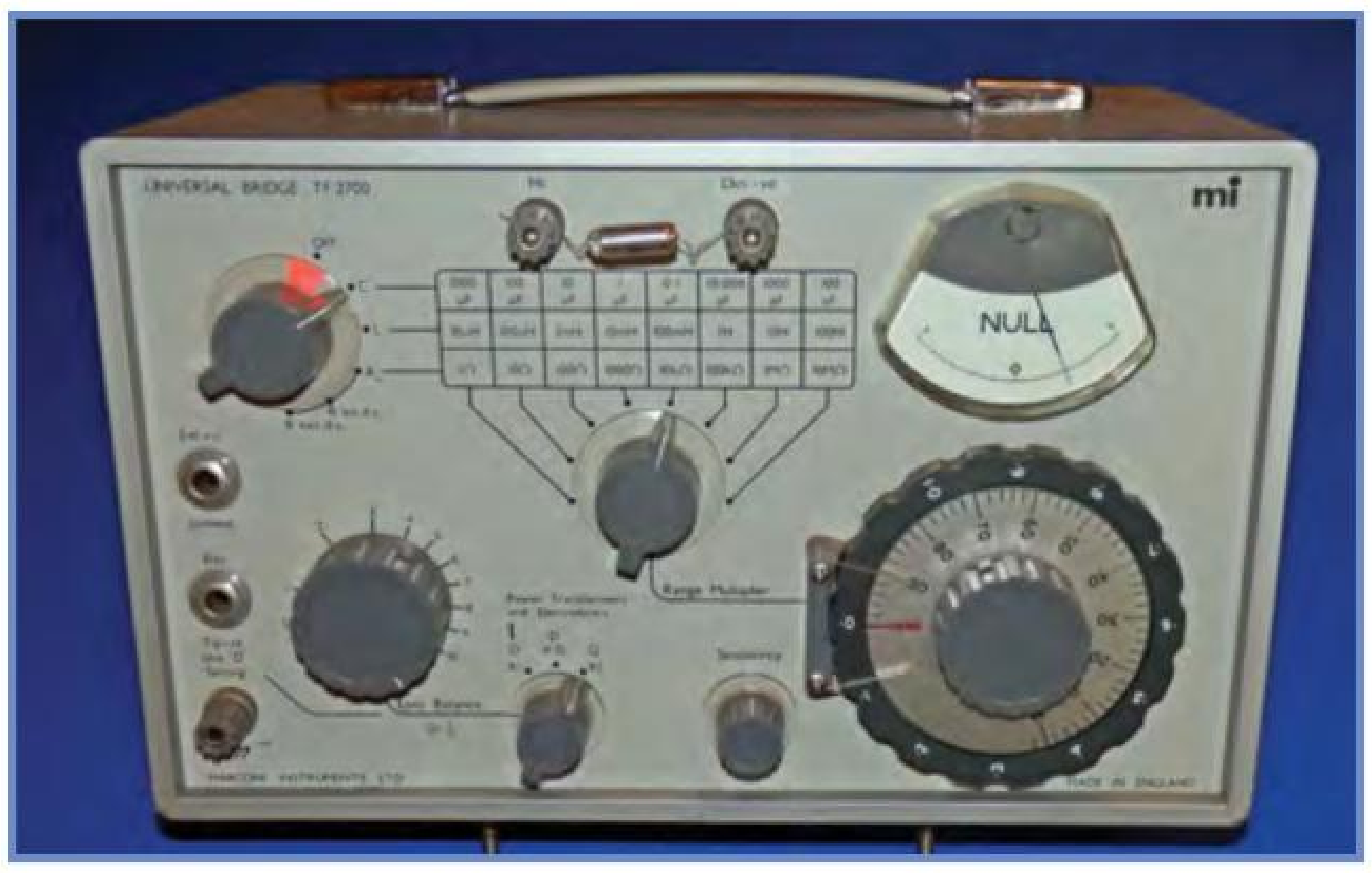


Fig.4.13 A Marconi Instruments TF2700 'universal' bridge being used to measure a polystyrene film capacitor. Note the 'null' meter, range switch and large adjustable variable control

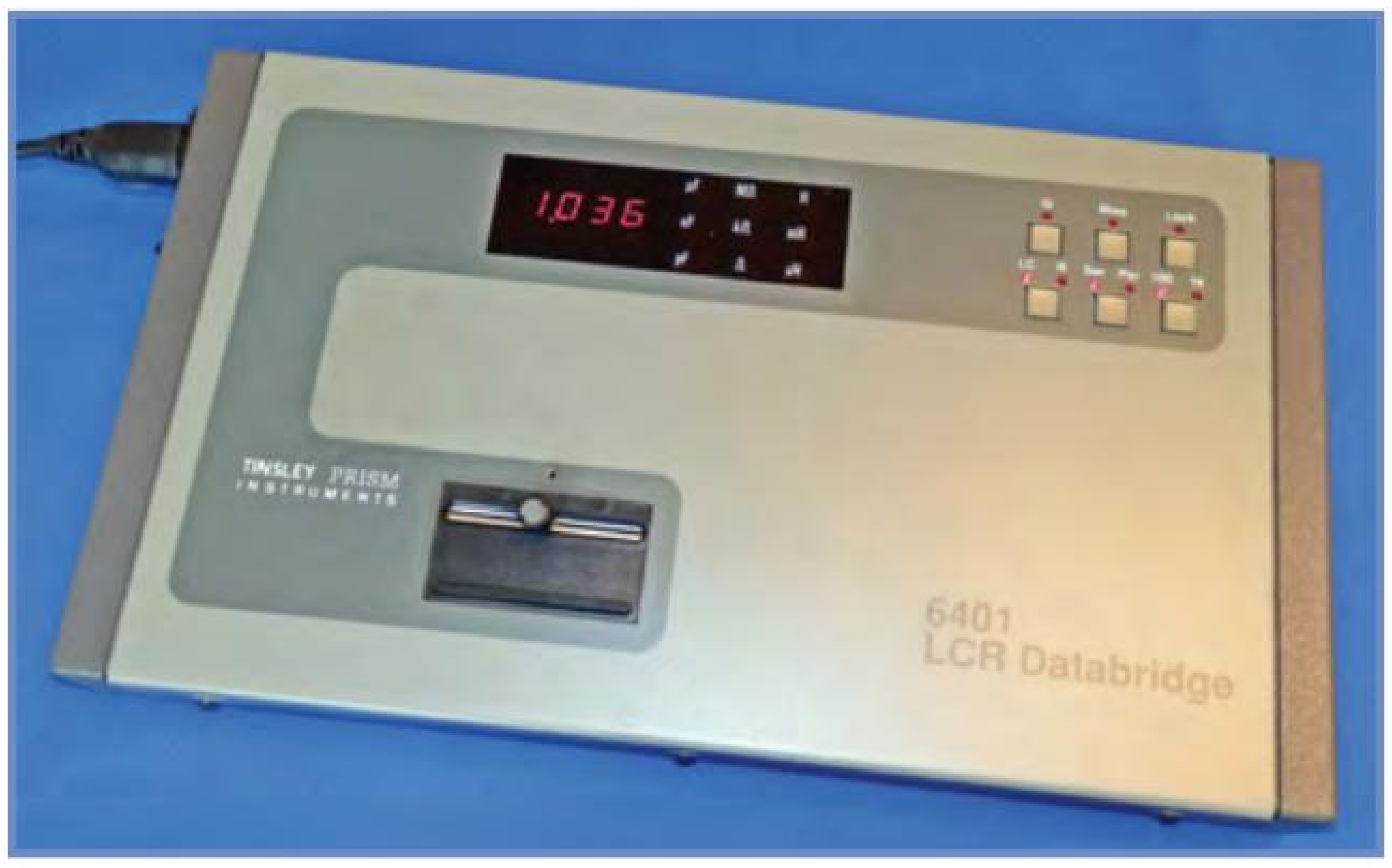


Fig.4.14 The Tinsley Prism LCR Databridge can measure a very wide range of resistance, capacitance and inductance with a basic accuracy of 2.5%

Table 4.5 Comparison of different component testers

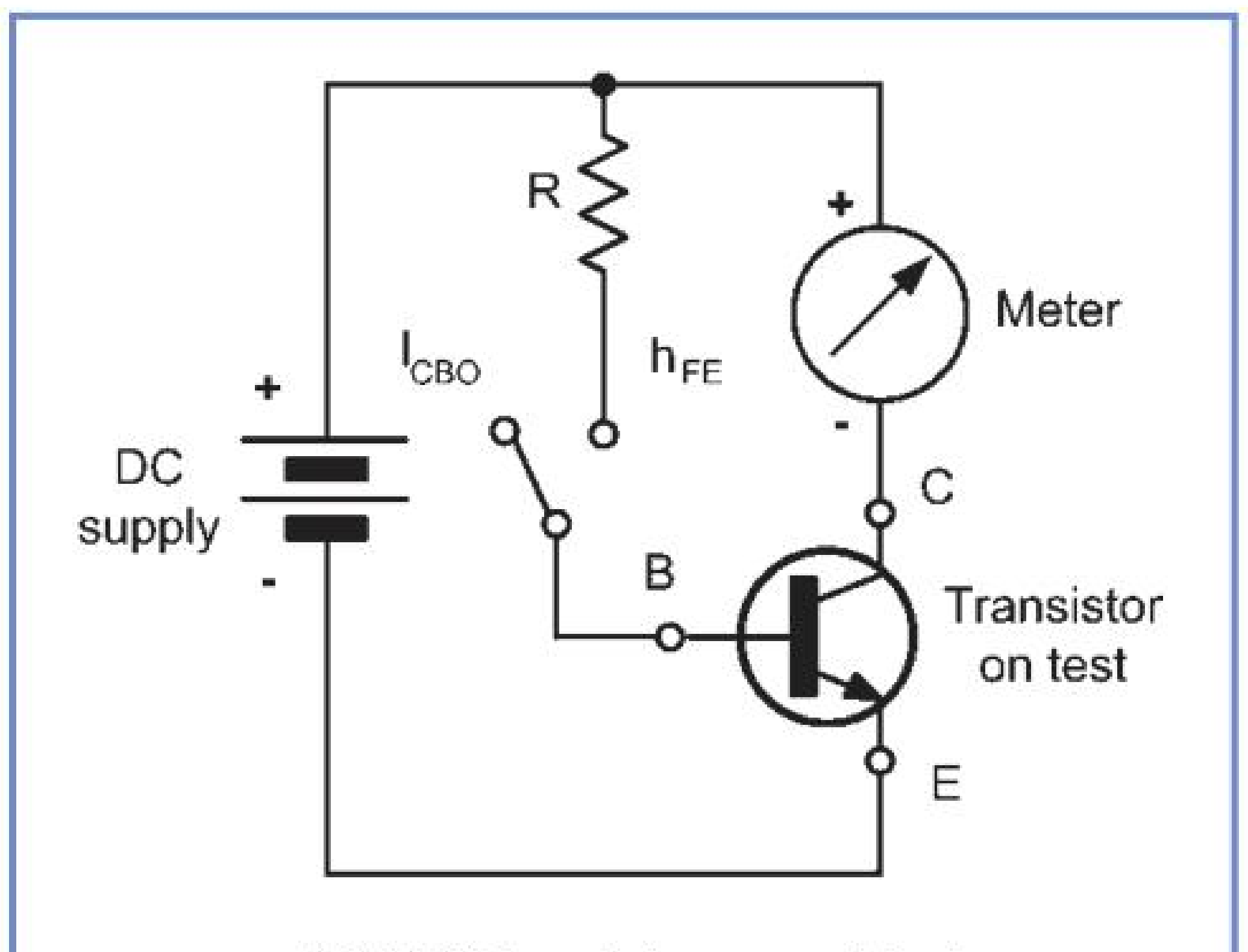
Component on test	Instrument	Indication	Notes
1kΩ 1% high-stability metal oxide resistor 0.2W	Tinsley Prism Automatic LCR Databridge	1000Ω	Test frequency 1kHz
	Marconi TF2700 Analogue LCR bridge	1.05kΩ	Used on DC
	Peak Electronics Atlas LCR40 component tester	999.1Ω	
	Vici VC99 auto-ranging digital multimeter	1.000kΩ	
10nF polystyrene 2% 150V	Tinsley Prism Automatic LCR Databridge	10.01nF	Test frequency 1kHz
	Marconi TF2700 Analogue LCR bridge	10.1nF	Used on AC 1kHz
	Peak Electronics Atlas LCR40 component tester	10.22nF	
	Vici VC99 auto-ranging digital multimeter	10.05nF	
60mH iron cored inductor 500mA/6Ω	Tinsley Prism Automatic LCR Databridge	56.84mH	Test frequency 1kHz
	Marconi TF2700 Analogue LCR bridge	90mH	No DC bias applied
	Peak Electronics Atlas LCR40 component tester	86.62mH in series with 5Ω	Test frequency 1kHz
	Vici VC99 auto-ranging digital multimeter	n.a.	No inductance range available

Automatic bridges can also be found from time to time at attractive prices on the second-hand market. The Tinsley Prism automatic 'Databridge' shown in Fig.4.14 is an example of one such instrument. It offers a basic accuracy of 0.25% and offers a measurement range extending from 0.1pF to 9900μF on the capacitance ranges, 0.1μH to 9900H on the inductance ranges, and 0.001Ω to 100MΩ on the resistance ranges. The instrument has a 5-digit LED display, measures Q and D, and has selectable measurement frequencies of 100Hz, 1kHz, 10kHz and 100Hz. Such an impressive specification comes at a price but you can still find second-hand instruments of this type (and similar instruments from other manufacturers such as Thandar) for less than £200.

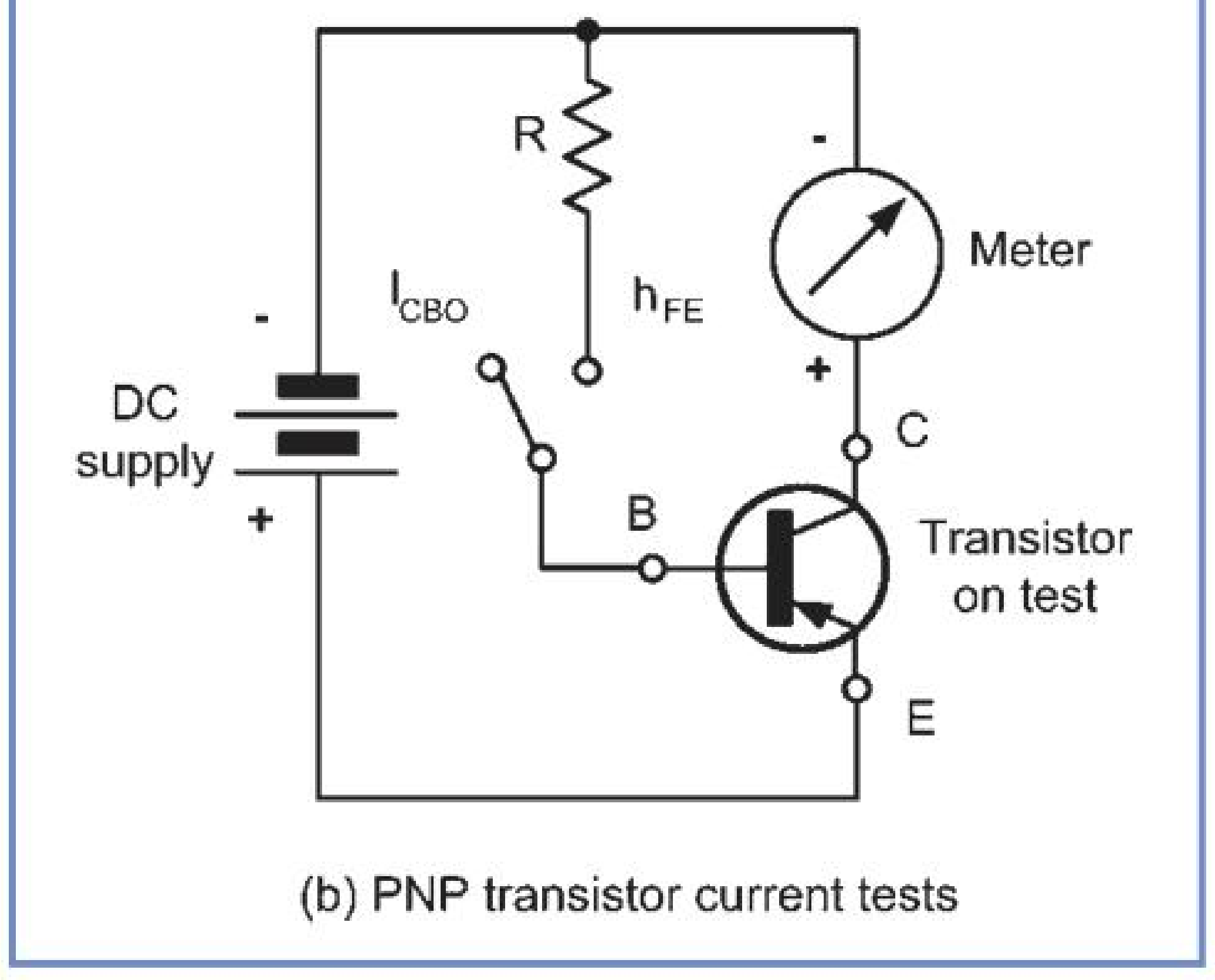
With such widely different specifications you might be wondering how the instruments that we've just described compare when making some everyday measurements. Table 4.5 shows the results of a comparison of four different instruments when measuring a 1% metal-oxide resistor of 1kΩ, a 10nF 2.5% polystyrene film capacitor, and a 60mH iron-cored inductor rated at 500mA/6Ω. These results speak for themselves!

Testing diodes and transistors

Most modern multimeters incorporate ranges suitable for testing diodes and transistors. Tests can be restricted to simple junction checks as well as



(a) NPN transistor current tests



(b) PNP transistor current tests

Fig.4.15 Principle of transistor testing for leakage current and current gain

Get it right when using component testers

- Check that the instrument is suitable for the job and that the expected value is well within the measuring range of the instrument
- Check that the instrument has been calibrated before use and also select an appropriate measurement frequency
- When using a hand-held component tester check that the battery voltage is within the nominal working range
- When using a 'universal' bridge select a higher range and work downwards, progressively increasing the sensitivity of the instrument in order to obtain a sharp null indication
- When using a 'universal' bridge don't forget to adjust the phase balance control for the sharpest null
- When measuring low value resistors ensure that your test lead connections have minimal resistance (try shorting the test prods out and measuring the resistance of your test leads alone!)
- When measuring large values of capacitance ensure that the component is fully discharged before connecting it to a test instrument
- When measuring small values of capacitance and inductance (i.e. less than 10pF and 10μH respectively) ensure that you use the shortest possible connections to the test instrument
- Don't rely on measurements where component values may be towards the end of the instrument's measuring range (accuracy will invariable be impaired as the instrument's limits are approached).

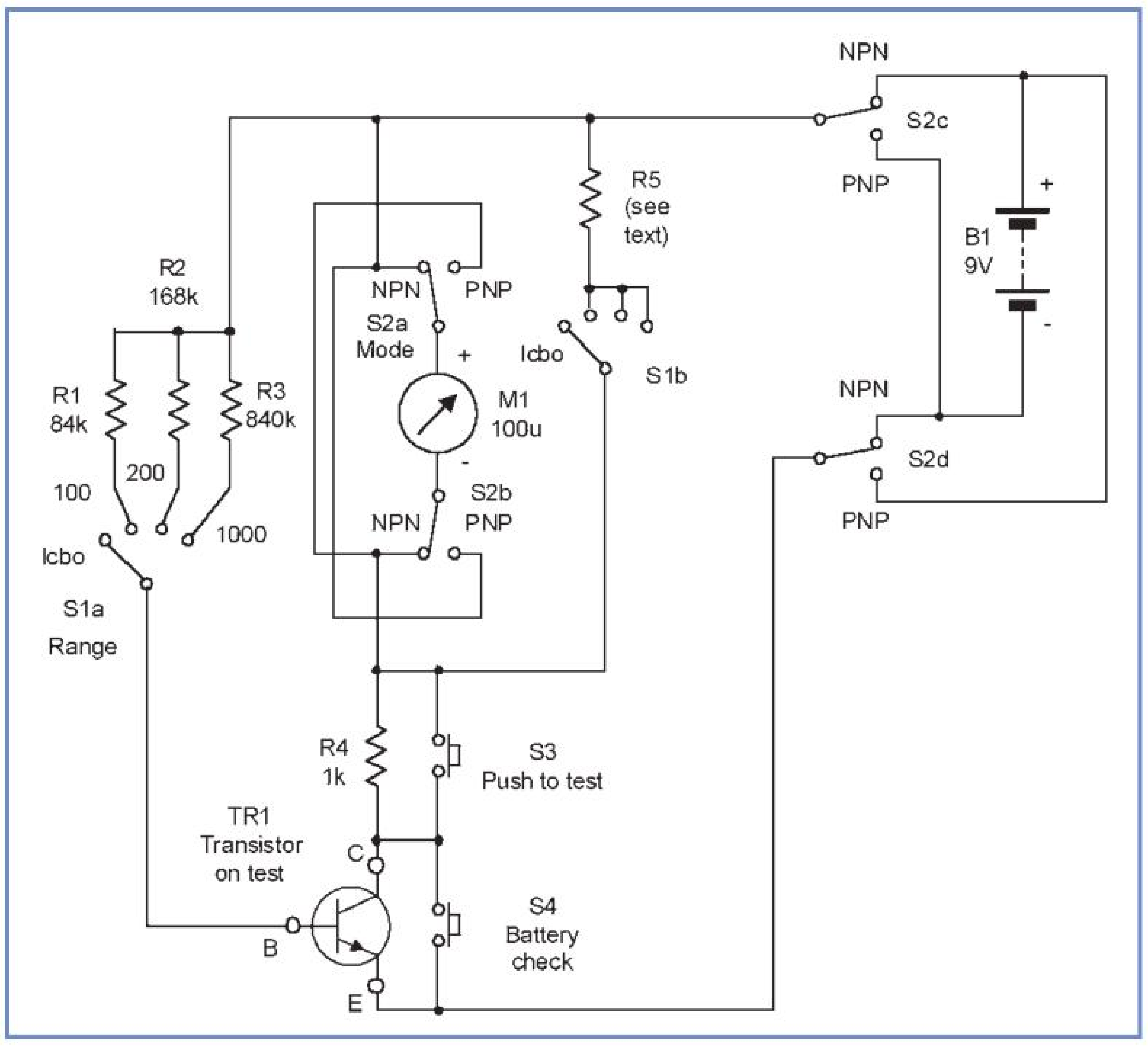


Fig.4.16 Simple transistor tester suitable for home construction

measurement of junction voltage and, in the case of bipolar transistors, measurement of current gain (h_{FE}). The principle of transistor current gain measurement for NPN and PNP junction transistors is illustrated in Fig.4.15. In each case, leakage current (I_{CBO}) is measured with no bias applied to the base connection. When current gain is to be measured a resistor, R, supplies current to the base of the transistor and the resulting collector current is displayed on the meter. If, for example, 0.1mA is applied to the base and 7.5mA is measured in the collector the current gain (under the prevailing conditions of V_{CE} and I_C) will be 75. The circuit of a simple transistor tester suitable for home construction is shown in Fig.4.16.

In addition to the use of a multimeter for simple checks (see Fig.4.17), dedicated transistor testers and analysers are available. Fig.4.18 shows the Peak Electronics semiconductor analyser at work. This versatile instrument can distinguish different types of diode and transistor and it will also identify their pin connections. If, like me, you have a large variety of unidentified or unmarked semiconductor devices in your workshop this gadget could be a real boon!

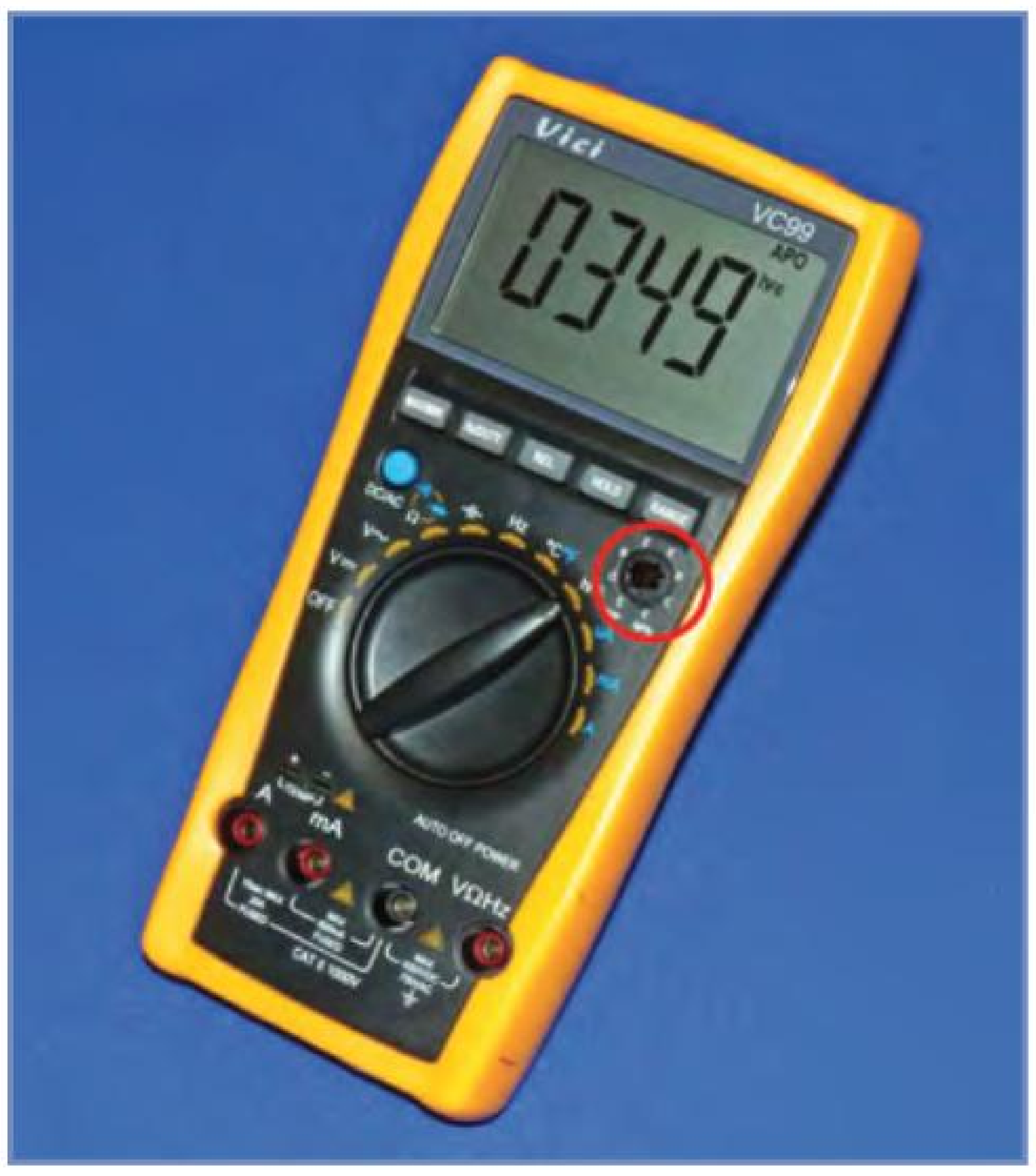


Fig.4.17 A low-cost multimeter being used to measure the current gain of a small-signal transistor inserted into the test socket (on the right-hand side of the instrument). The instrument is indicating a current gain (h_{FE}) of 381

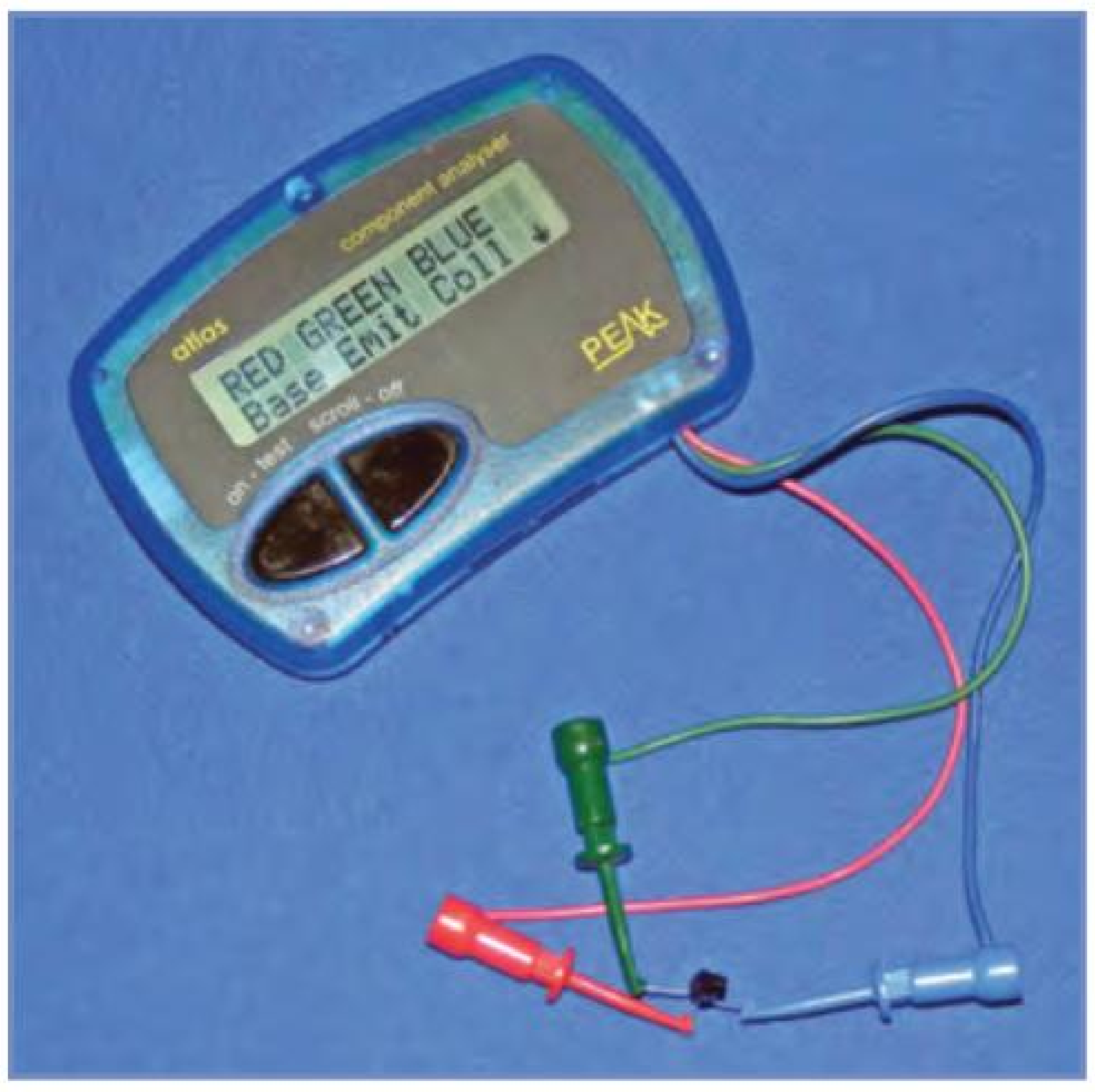


Fig.4.18 The Peak Electronics semiconductor analyser at work. Note it has identified the pin connections of the transistor on test. Further data on the device, such as junction configuration and current gain is available by scrolling the display

Test Gear Project: A semiconductor junction tester

When testing an unknown component, you might be tempted to connect a voltage source and simply measure the current flowing. This is ideal for measuring resistors but it's inappropriate for testing semiconductor junctions because of their constant-voltage characteristics. A much better technique is that of applying a constant current (rather than a constant voltage) before measuring the voltage that's developed across the junction. Since the junction is polarity conscious, it allows the functional state to be checked. It also allows you to measure the junction voltage safely which, in turn, can yield further useful information.

The complete circuit of our *Test Gear Project* is shown in Fig.4.19. The circuit is very simple and uses only a handful of inexpensive components. The circuit comprises a precision constant-current source with switched resistors, R2 and R3, used to set the current produced to either 1mA (R2) or 10mA (R3). Red and green LEDs (D1 and D2 respectively) are used to indicate the input and output voltage of the constant-current source (note that when no current is supplied the output voltage (V_{out}) will be very close to the input voltage (V_{in}).

You will need

1	Perforated copper stripboard (9 strips, each with 25 holes)
2	2-way miniature terminal blocks
1	ABS case with integral battery compartment
1	9V PP3 battery clip
1	9V PP3 battery
2	3-pin PCB headers
1	Miniature DPDT toggle switch with centre-off (S1)
1	red 2mm panel-mounting socket (SK1)
1	black 2mm panel-mounting socket (SK2)
1	LM334 8-pin DIL constant-current source (IC1)
1	8-pin low-profile DIL socket
1	5mm red LED (D1)
1	5mm green LED (D3)
1	1N4148 diode (D2)
1	1kΩ resistor (R1)
1	68Ω resistor (R2)
1	6.8Ω resistor (R3)
1	100n 63V miniature polyester capacitor (C1)

Assembly

Assembly is straightforward and should follow the component layout shown in Fig.4.20. Note that the yellow stripe

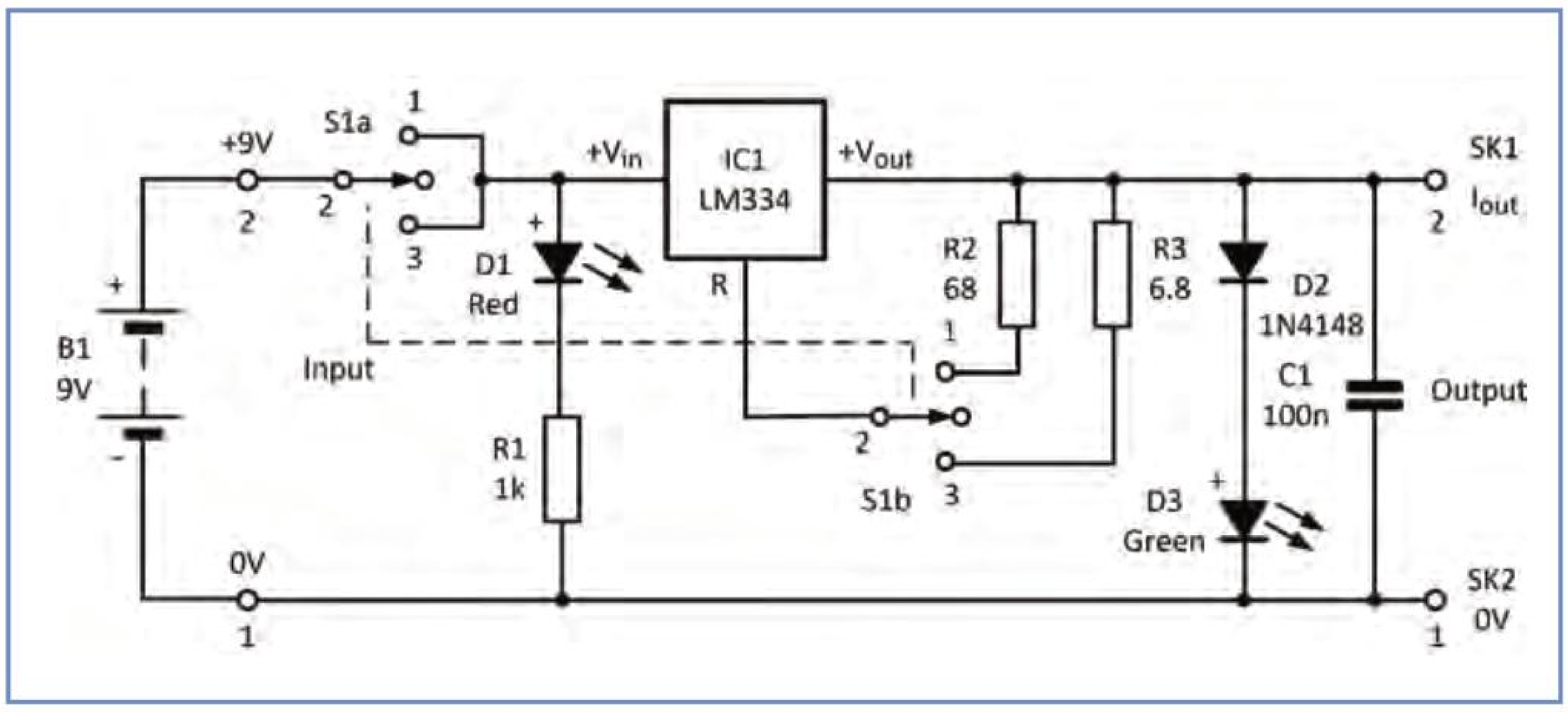


Fig.4.19 Complete circuit of the semiconductor junction tester

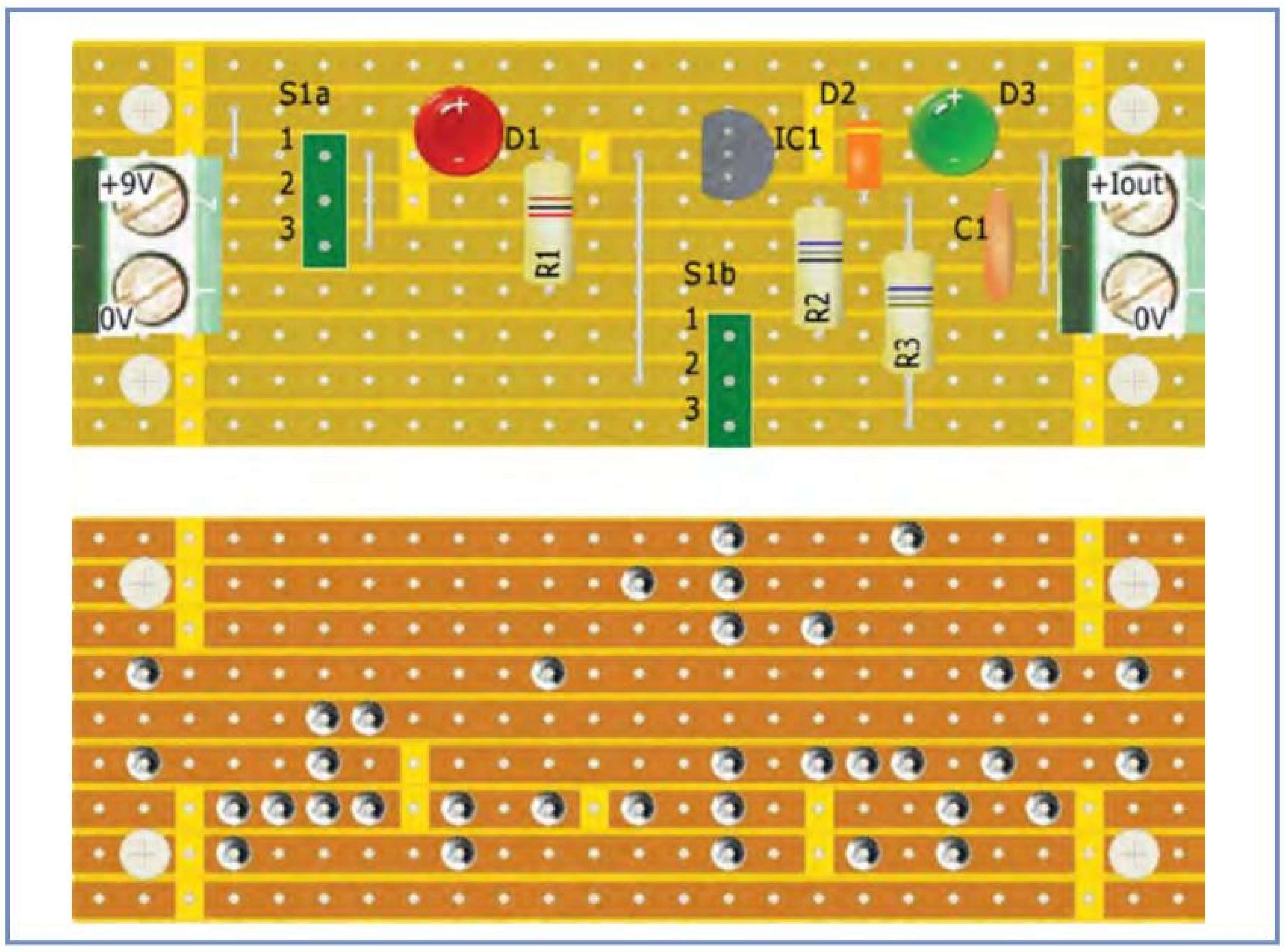


Fig.4.20 Stripboard layout of the semiconductor junction tester

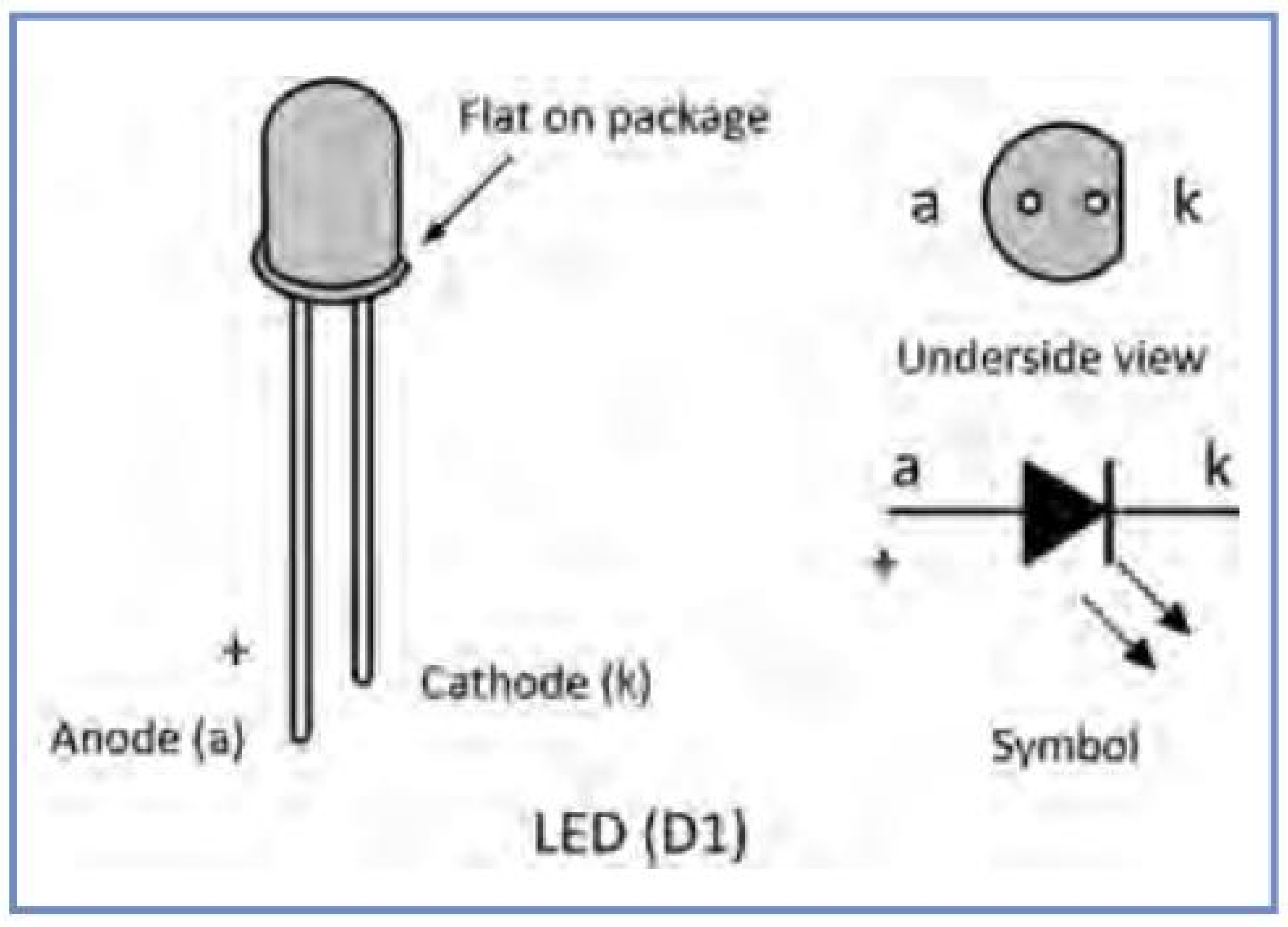


Fig.4.21. LED pin connections

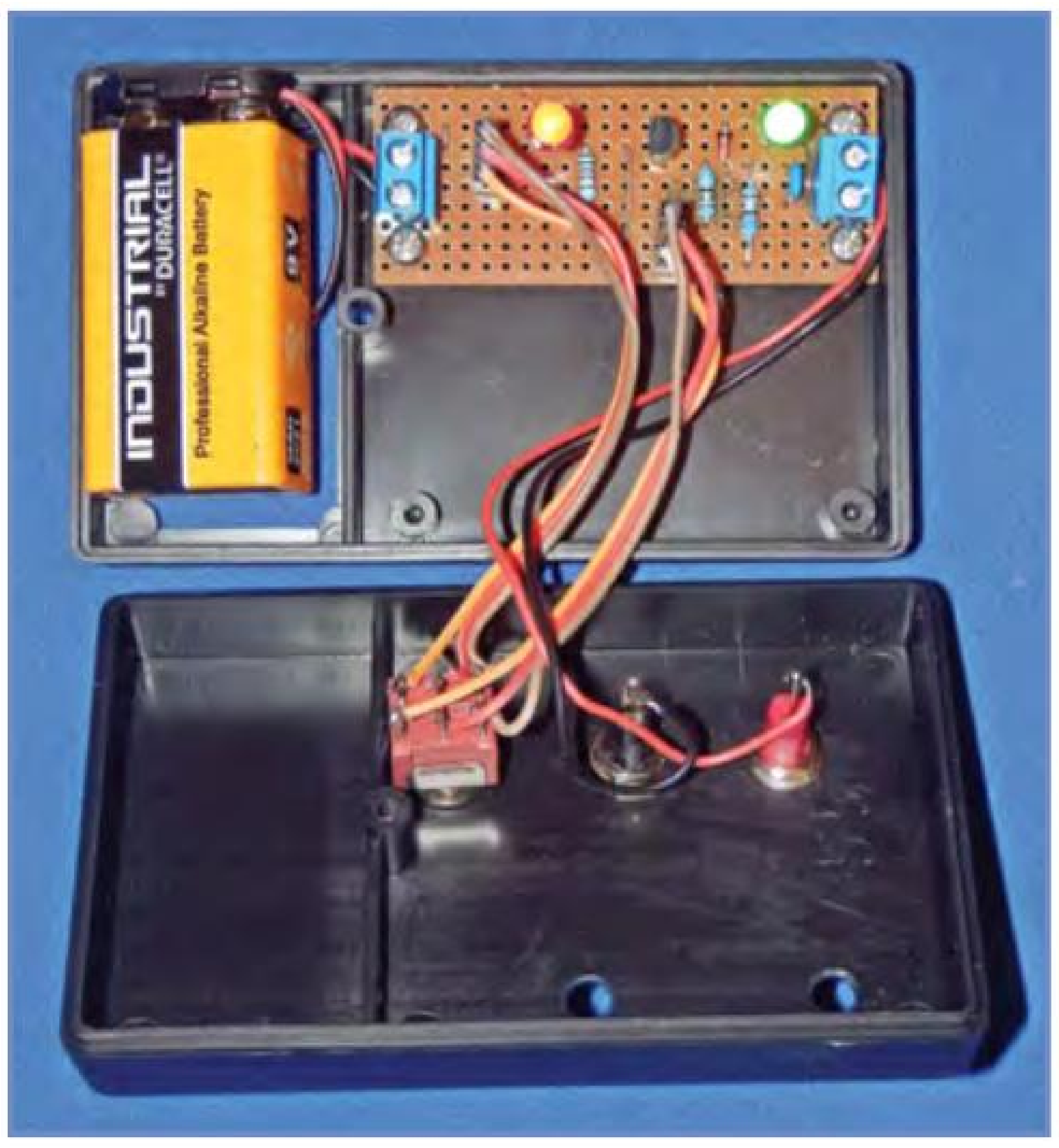


Fig.4.22 Internal wiring of the semiconductor junction tester

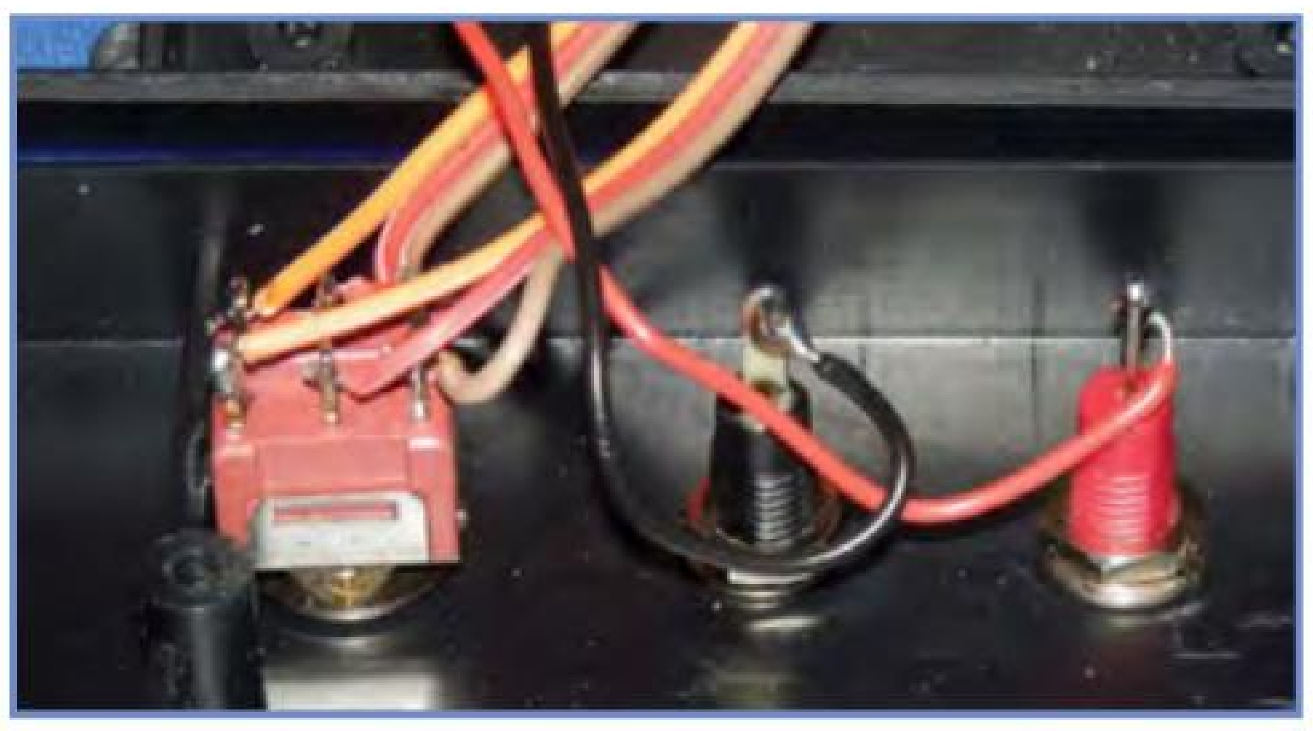


Fig.4.23 Rear panel wiring

on D2 marks the cathode connection. While the '+' symbol shown on D1 and D2 indicates the more positive (anode) terminal of the two LEDs. The pin connections for the LEDs are shown. The reverse side of the board (*not* an X-ray view) is also shown in Fig.4.20. Note that there's a total of 17 track breaks to be made. These can be made either with a purpose-designed spot-face cutter or using a small drill bit of appropriate size. There are also four links made with tinned copper wire of a suitable diameter or gauge (eg, 0.6mm/24SWG). When soldering has been completed it is very important to carry out a careful visual check of the board as well as an examination of the track side of the board looking for solder splashes and unwanted links between tracks. The internal and rear panel wiring of the semiconductor junction tester is shown in Fig.4.22 and Fig.4.23 respectively.

Setting up

No setting up is required after assembly – all you need to do is to connect a PP3 battery and switch on! D1 and D3 should both become illuminated. If not, check the battery and circuit connections carefully. Next, connect the output (SK1 and SK2) via red and black test leads to your digital multimeter. Select a 1mA test current via S1 and set the multimeter to the 20mA DC range. The meter should indicate a current of exactly 1mA. If not, switch off and carefully check your wiring and PCB layout. Next, select a 10mA test current and check that the meter indication is between 9.5mA and 10mA (depending on the state of the battery it may not be exactly 10mA).

Table 4.6 Typical test results for various types of diode

Component on test	Connection polarity	Test current	Indication
1N4148 general purpose silicon diode	Forward: + (red) to anode, – (black) to cathode	1mA	0.625V
		10mA	0.742V
	Reverse: + (red) to cathode, – (black) to anode	1mA	Reverse LED
		10mA	Reverse LED
1N34 germanium signal diode	Forward: + (red) to anode, – (black) to cathode	1mA	0.304V
		10mA	0.525V
	Reverse: + (red) to cathode, – (black) to anode	1mA	Reverse LED
		10mA	Reverse LED
BA579 PIN diode	Forward: + (red) to anode, – (black) to cathode	1mA	0.642V
		10mA	0.760V
	Reverse: + (red) to cathode, – (black) to anode	1mA	Reverse LED
		10mA	Reverse LED
1N4005 high-voltage diode	Forward: + (red) to anode, – (black) to cathode	1mA	0.555V
		10mA	0.670V
	Reverse: + (red) to cathode, – (black) to anode	1mA	Reverse LED
		10mA	Reverse LED
1N538 silicon power diode	Forward: + (red) to anode, – (black) to cathode	1mA	0.562V
		10mA	0.632V
	Reverse: + (red) to cathode, – (black) to anode	1mA	Reverse LED
		10mA	Reverse LED
BZX55 Zener diode C2V7	Forward: + (red) to anode, – (black) to cathode	1mA	0.729V
		10mA	0.805V
	Reverse: + (red) to cathode, – (black) to anode	1mA	Reverse LED
		10mA	Reverse LED
Red 0.2-inch LED	Forward: + (red) to anode, – (black) to cathode	1mA	1.79V
		10mA	1.94V
	Reverse: + (red) to cathode, – (black) to anode	1mA	Reverse LED
		10mA	Reverse LED
Green 0.2-inch LED	Forward: + (red) to anode, – (black) to cathode	1mA	2.37V
		10mA	2.72V
	Reverse: + (red) to cathode, – (black) to anode	1mA	Reverse LED
		10mA	Reverse LED

Fig.4.26 shows the test procedure for checking a silicon diode. The green LED (D2) will be illuminated

when the diode is non-conducting (ie, reverse biased) but will be extinguished when the diode is conducting (ie, forward biased). This will allow you to identify the diode's anode and cathode connections (as shown in Fig.4.26). If desired, you can measure the junction voltage in the forward and reverse biased states. Table 4.6 shows typical test results for a variety of common diodes and LEDs.

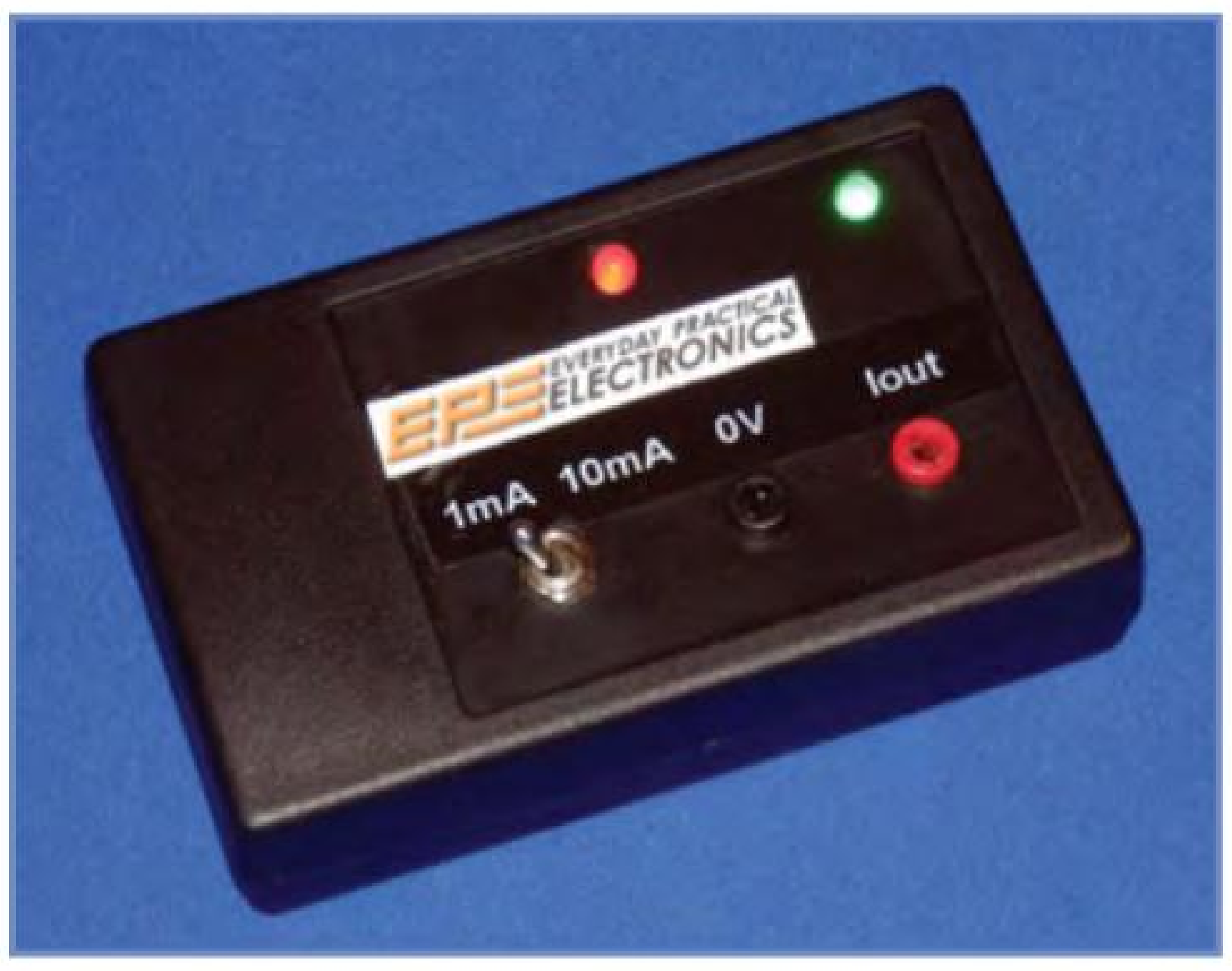


Fig.4.24 External appearance of the finished semiconductor junction tester

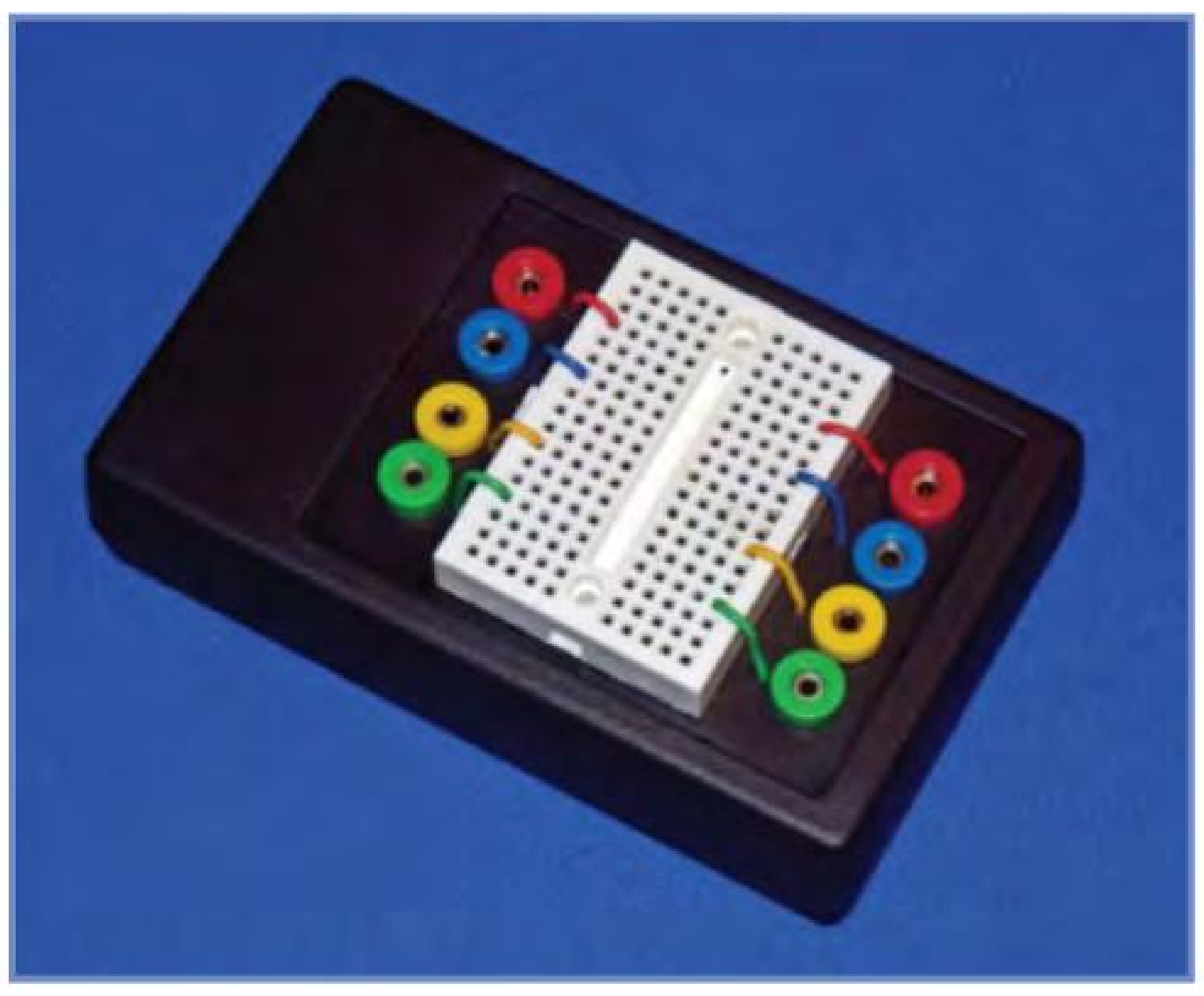


Fig.4.25 Breadboard test fixture

For junction testing it can be convenient to make use of a breadboard test fixture like that shown in Fig.4.25. Fig.4.27 shows the junctions of a TO92 transistor being tested, while Table 4.7 shows typical test results for a variety of common transistors.

Next month

In next month's *Teach-In 2018 – Part 5* – we will be looking at inductors, resonant circuits and quartz crystals. Our practical project will feature a useful crystal checker that can also be used as a handy calibration source. We will also be introducing Q-measurement and the use of a dip meter for checking tuned circuits.

Table 4.7 Typical test results for various types of transistor

Component on test	Connection polarity	Test current	Indication
BC548 general purpose NPN transistor	Forward: + (red) to base, – (black) to emitter	1mA	0.720V
		10mA	0.817V
	Reverse: + (red) to emitter, – (black) to base	1mA	Reverse LED
		10mA	Reverse LED
	Forward: + (red) to base, – (black) to collector	1mA	0.715V
		10mA	0.798V
	Reverse: + (red) to base, – (black) to collector	1mA	Reverse LED
		10mA	Reverse LED
BC327 general purpose PNP transistor	Forward: + (red) to emitter, – (black) to base	1mA	0.666V
		10mA	0.769V
	Reverse: + (red) to base, – (black) to emitter	1mA	Reverse LED
		10mA	Reverse LED
	Forward: + (red) to collector, – (black) to base	1mA	0.671V
		10mA	0.722V
	Reverse: + (red) to base, – (black) to collector	1mA	Reverse LED
		10mA	Reverse LED
BU508 high-voltage NPN power transistor	Forward: + (red) to base, – (black) to emitter	1mA	0.498V
		10mA	0.621V
	Reverse: + (red) to emitter, – (black) to base	1mA	Reverse LED
		10mA	Reverse LED
	Forward: + (red) to base, – (black) to collector	1mA	0.546V
		10mA	0.633V
	Reverse: + (red) to base, – (black) to collector	1mA	Reverse LED
		10mA	Reverse LED

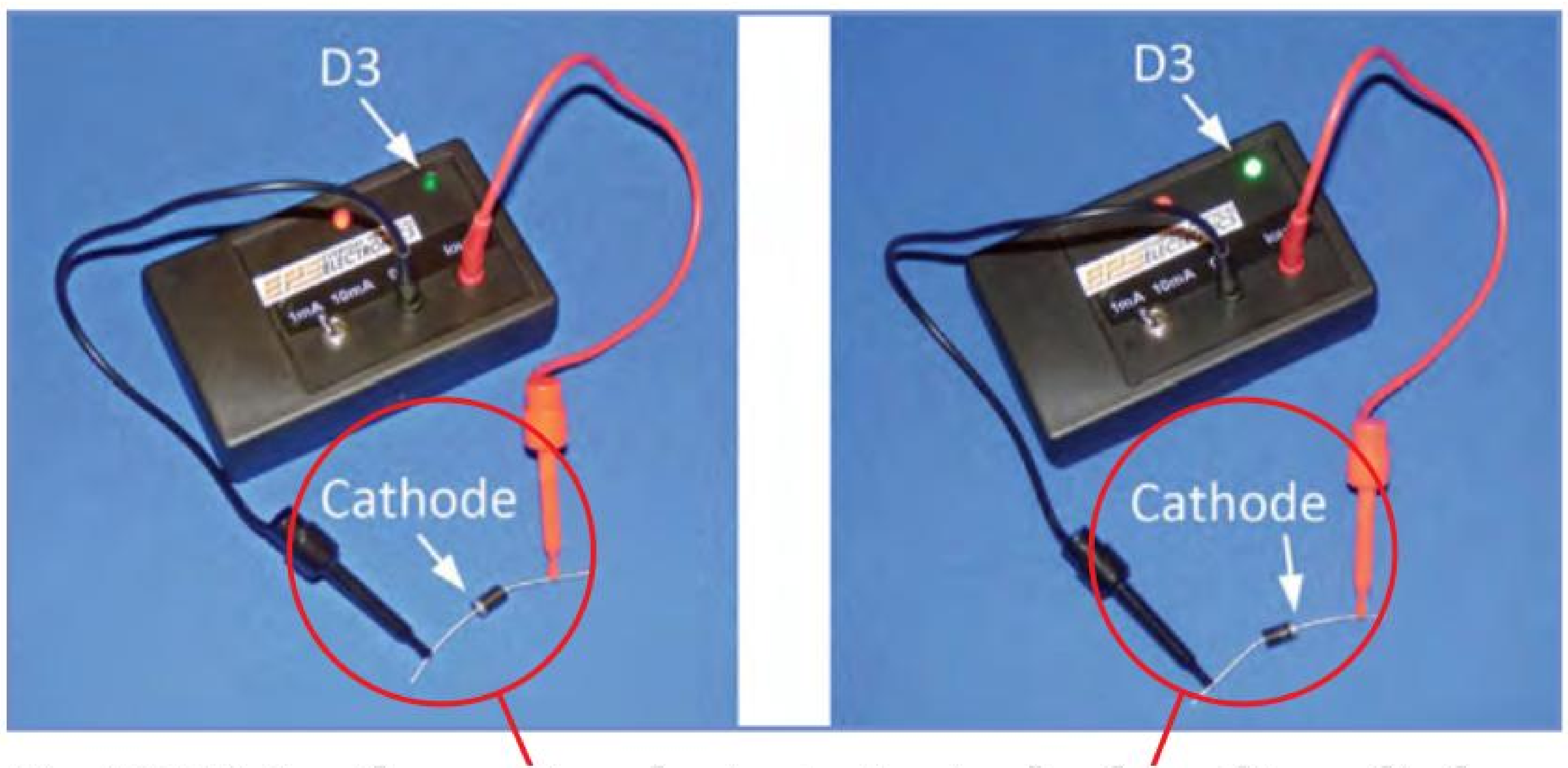
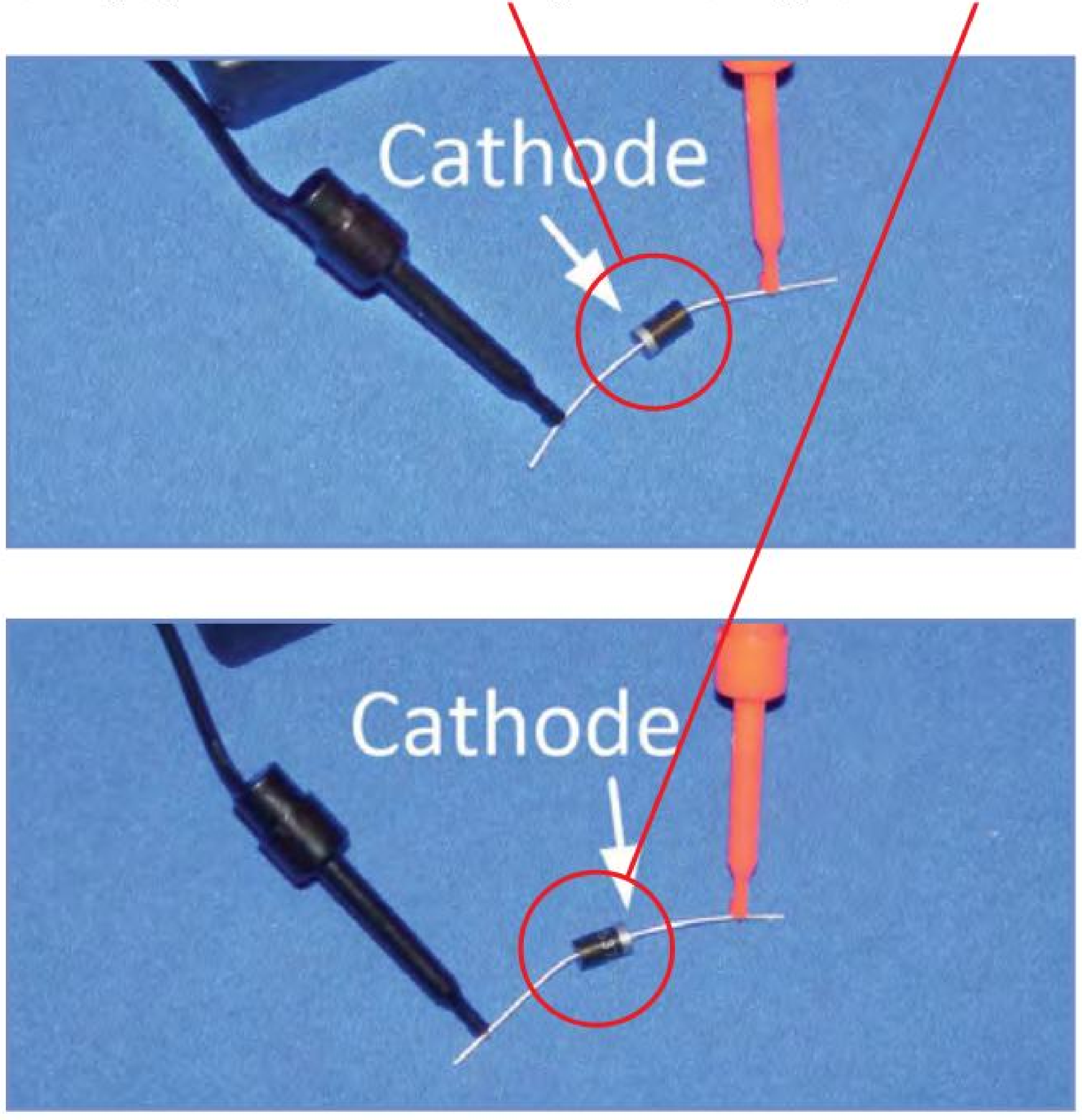


Fig.4.26 Using the semiconductor tester to check a silicon diode: a) (left) forward conducting and b) (right) reverse non-conducting



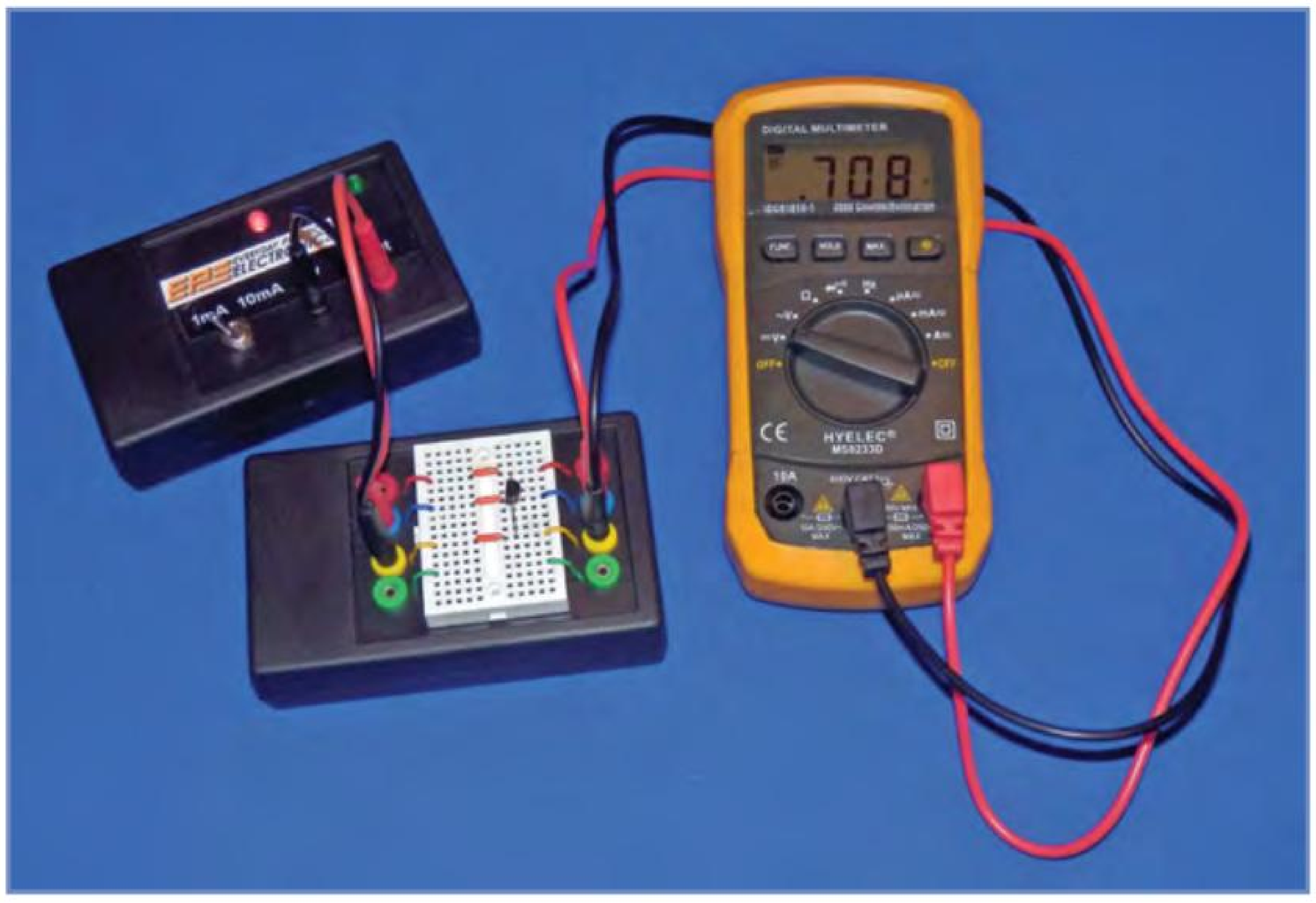


Fig.4.27 Using the semiconductor tester and breadboard test fixture to check a transistor

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NET WORK

by Alan Winstanley

Faster still

BRITISH READERS will be familiar with the retail phenomenon known as the 'Argos catalogue', a mighty 1,800-page full-colour tome weighing some 3½ pounds (1.6kg) which lists the entire range of retail products sold by the Argos store chain (**www.argos.co.uk**). Buying from Argos is a rite of passage for British consumers: after sifting through the catalogue or scrolling the store's touchscreen displays to choose, you pay at a machine and queue up at the designated counter to await your goods. On a good day this service can be fast and convenient, although there is the hassle of driving there and back again.

So when the power cord on the family's electric iron started to fall off, a satisfying Sunday morning was spent (as you would expect) dismantling it to see whether a new one could be fitted. Sadly, defeated by some fiendish crimp terminals devised by Bosch, there was nothing for it but to conclude a new electric iron was needed. Heading for the sofa, I decided that rather than thumbing through a humongous catalogue, a more sensible idea was to flick through the Argos app on an Android tablet. Before long, a new iron was selected online, encouraged by the timely reviews of happy customers. Naturally, these days, it's now second-nature to surf around to see if a better deal can be had elsewhere. However, one thing that's hard to compete with is the Argos 'Fast Track' service. It offers same-day delivery on some items for just £3.95 if you order by 6pm. I decided to try it – 'sold, to the man on the sofa!'

In fact, for any online 'heavy lifting' (eg, entering payment details and sorting out delivery), I much prefer to use a PC and mouse rather than a phone or tablet, and so an order was duly completed online. Would Argos deliver on its Fast Track promise? Absolutely – a few hours later a cheery Argos driver handed me a new electric iron over my garden gate. It was a faultless service and an invaluable, time and fuel-saving one as well.

Flushed with success

Living on an island like Great Britain, delivery distances are much shorter compared with, say, the US, and in years to come, online ordering and same-day deliveries will probably be the norm. Amazon already holds out the prospect of same-day deliveries to customers who use its Prime programme, but this is restricted to major British conurbation areas and is beyond the reach of rural locations. Amazon 'Prime Now' aims for two-hour deliveries of many consumables.

Entire online industries continue to sharpen their offer with deliveries to your chosen post office, convenience store, filling station or 'Amazon Locker'. A year ago, some beta trials of Amazon 'Prime Air' in England used a flying drone with GPS to successfully deliver a small packet to an open rural location. Amazon eventually hopes to automatically despatch such drones in suitable localities, a service that would be ideal for more remote areas once the logistics and aviation considerations can be overcome. Meanwhile, to make online ordering more seamless still, Amazon UK recently doubled to 100 its range of stick-on Wi-Fi Dash buttons (see *Net Work*, December 2016), offering one-click ordering of popular household consumables, though some products seem costly. The most popular items re-ordered this way are toilet rolls, followed by dishwasher tablets, says Amazon.

Join us on EEWeb

Regular readers will know that after many years of service the *EPE Chat Zone* forum (**www.chatzones.co.uk**) has sadly reached its end of life. With legacy software and server compatibility problems looming, the decision to set it to 'read-only' mode has reluctantly been made. We have been very keen to keep our online community together and, helped in no small measure by Clive 'Cool Beans' Maxfield, we are pleased to announce that the website **EEWeb.com**, part of the AspenCore network that provides content and online tools for electronic engineering websites, has graciously agreed to host a new forum specially for *EPE* readers.

Readers might not have heard of AspenCore, but they are the name behind some very well-known websites such as *EE Times*, *EDN Network*, **embedded.com**, **Elektroda.pl** and **datasheets.com**. The *EEWeb* site itself is peer-driven and was specially designed to appeal to users of electronic design tools. As well as providing a suite of free design, verification, and analysis tools, EEWeb is the home for experienced and novice designers to share tips and to ask and answer questions, says AspenCore. We feel it's an ideal partnership and *EPE* readers of all abilities will feel right at home. We hope the new, modern surroundings will enable our followers to interact with a whole new audience as well as broadening the range of topics and discussions in which they can participate.

To access *EEWeb* forums, simply visit **EEWeb.com** and in the menu follow **Our Community/Forums**. This leads to the main **Electronics and Electrical Engineering Design Forum** page where the most recent questions posted on *EEWeb* are listed first. To navigate to *EPE Magazine's* area, you can go to our sub-topic (main web page, right-hand column) which *EEWeb* has kindly offered us as our new home. You can also go directly to **www.eeweb.com/forum/tags/epe-magazine**. It will be seen that *EEWeb's* contents are organised by broad 'Categories' or engineering disciplines first, with sub-topics providing a more granular breakdown of content.

Tag teams

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EPE is very grateful to AspenCore for graciously welcoming us on board and we hope the new forum will benefit readers looking to engage with the online engineering community. The legacy *EPE Chat Zone* will remain, for the forseeable future, as a source of reference for older issues and projects. Please do join us on *EEWeb* and help make our new forum a vibrant and successful one.

Happy Christmas!

I'll close by thanking all our readers for their continued support and *EPE* wishes you all a happy and peaceful Christmas. Join us again in the New Year!

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PIC n' Mix

Mike O'Keeffe

Our periodic column for PIC programming enlightenment

Four-digit, seven-segment LED display – Part 2

IN THIS column, we are continuing work on the four-digit seven-segment display we started last month, by focusing on the software to control the display. There's quite a bit of setup in the code and to make things a little easier, we're going to use Microchip's Code Configurator (MCC), which we discussed back in the November edition. The code configurator will be used to configure easy-to-use pin names, timers and interrupts, allowing us to focus on the functionality.

I explained last month that controlling the display is tricky because of the pin reduction techniques used in the seven-segment display. Common-cathode or common-anode displays connect (ie, 'common') all the cathodes or anodes of a single digit together to reduce the number of pins. Fig.1 depicts the relevant inputs for the display. Each unique segment is also connected to each digit; segment 'a' on the first digit is connected to the second, third and fourth digits as well. This reduces a possible pin count of 56 pins down to 11. The complication arises when we want to display two different numbers on separate digits. Without some clever timing in the code, the display might end up showing the same number on every digit.

The classic 24-hour clock

Now we're going to look at how to control the display, but first we need to choose something to put on the display. Let's make a 24-hour clock. Unlike the clock on your home cooker, this one will not always be flashing; it will be programmed and always working (at least until the battery fails). We have four digits and a semicolon, so we should be able to display the hours and minutes easily enough. Our code only needs to update the display every minute, while it counts the seconds in the background.

For our 24-hour clock to work, we need to use a timer that will give us our seconds. Remember, we have four digits and we will technically only be showing one at a time, albeit for a very short time. Our (single) minutes will be the right most digit (digit 4) in Fig.1. The tens of minutes will be displayed in digit 3; hours in digit 2 and tens of hours in the left-most digit (digit 1). Whenever the counter reaches 60 seconds, the clock increments the minutes.

Next, the code checks if the number of minutes exceeds 9 and if it does, it increments the tens of minutes. The tens of minutes will increment the hours if it exceeds 5 (60 minutes in an hour, thus 59 is the maximum value). Likewise, the code checks if the hours exceeds 9 and increments the tens of hours if necessary. Last, the tens of hours code has to do a double check because it's looking for 24 hours, not 29. So, if the tens of hours is 2 and the hours exceeds 3, then it's midnight and the clock resets and starts all over again. Fig.2 shows the flow diagram of how the program will operate. In the main `while` loop, it checks if the seconds has exceeded 59 seconds, if not then it rotates around, displaying the digits on the display.

Setting up the GPIOs

MCC simplifies a lot of the coding tasks. Each GPIO can be setup with an individual name, set as an input or output and we can also select the default state. For the clock code, I've named each of the segment controls from 'a' to 'g' as `SEGA` to `SEGG`. These will be outputs. Each of the common cathodes will be called `CD1` to `CD4`. See Fig.3 as a snapshot for setting up all of the segments and common cathodes. By default, the name of each GPIO is the pin name, but we can set these to custom names to make our code easier to understand. `SEGL1L2` and the corresponding `CDL1L2` represent the semicolon. `SEGL3` and `CDL3` represent the apostrophe between

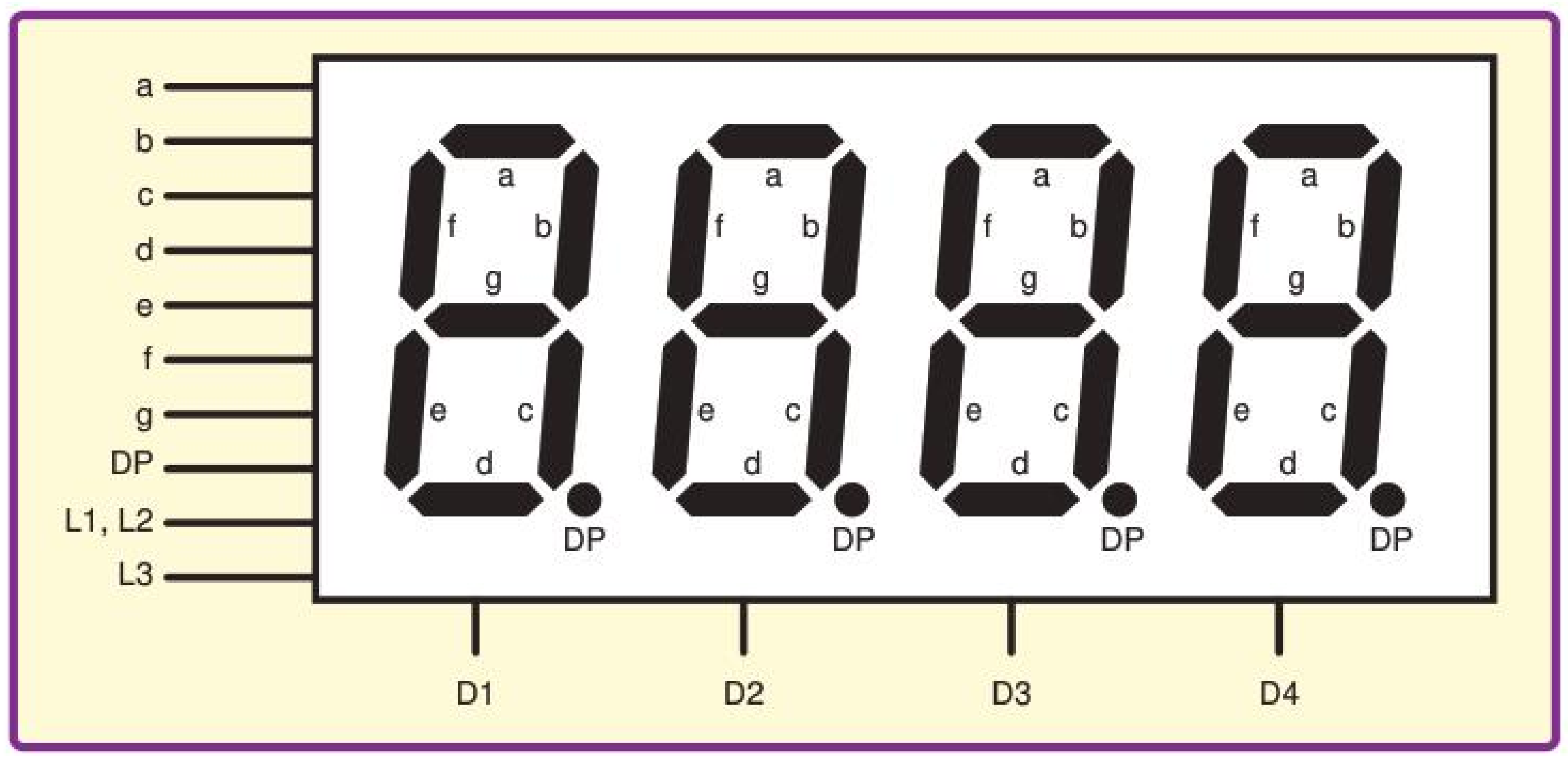

a
b
c
d
e
f
g
DP
L1, L2
L3
a
b
c
d
e
f
g
DP
D1
D2
D3
D4

Fig.1. Four-digit, seven-segment display pinout

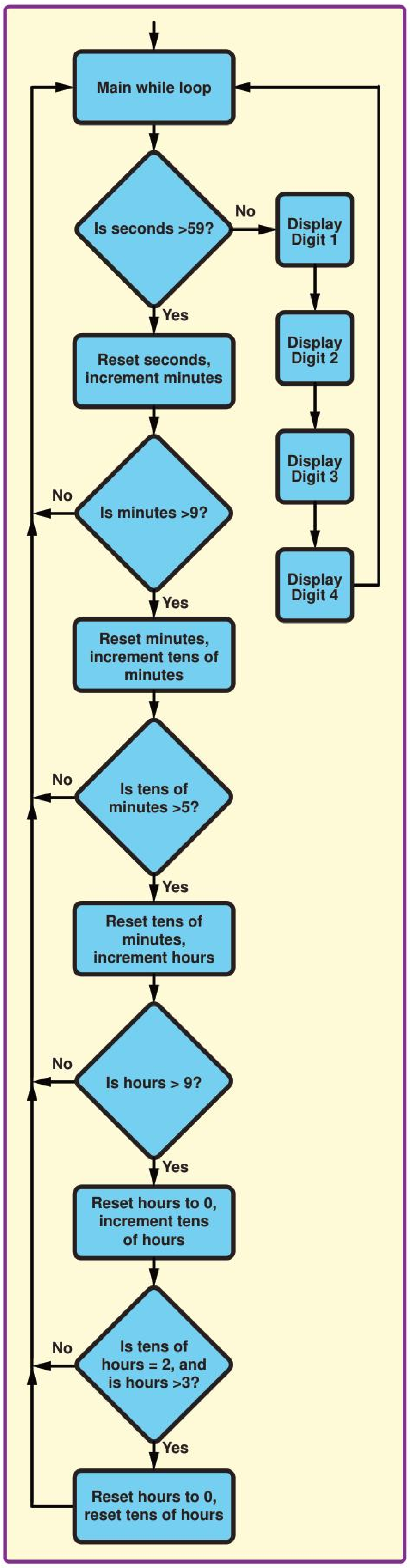
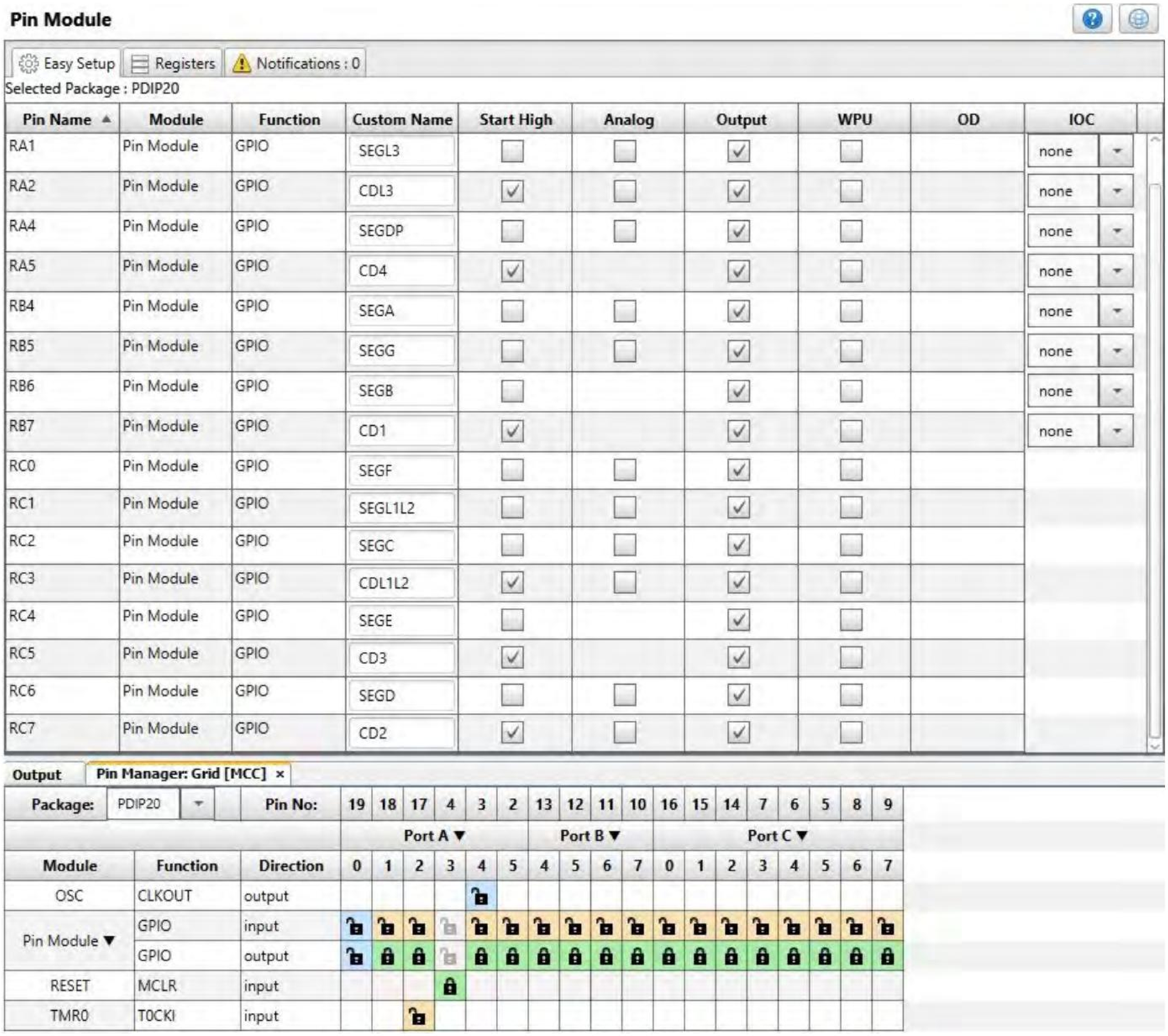

Main while loop
Is seconds >59?
No
Yes
Display Digit 1
Display Digit 2
Display Digit 3
Display Digit 4
Reset seconds, increment minutes
Is minutes >9?
No
Yes
Reset minutes, increment tens of minutes
Is tens of minutes >5?
No
Yes
Reset tens of minutes, increment hours
Is hours > 9?
No
Yes
Reset hours to 0, increment tens of hours
Is tens of hours = 2, and is hours >3?
No
Yes
Reset hours to 0, reset tens of hours

Fig.2. 24-hour Clock flow chart



Selected Package : PDIP20

Pin Name ▲	Module	Function	Custom Name	Start High	Analog	Output	WPU	OD	IOC
RA1	Pin Module	GPIO	SEGL3	☐	☐	☑	☐		none
RA2	Pin Module	GPIO	CDL3	☑	☐	☑	☐		none
RA4	Pin Module	GPIO	SEGDP	☐	☐	☑	☐		none
RA5	Pin Module	GPIO	CD4	☑		☑	☐		none
RB4	Pin Module	GPIO	SEGA	☐	☐	☑	☐		none
RB5	Pin Module	GPIO	SEGG	☐	☐	☑	☐		none
RB6	Pin Module	GPIO	SEGB	☐		☑	☐		none
RB7	Pin Module	GPIO	CD1	☑		☑	☐		none
RC0	Pin Module	GPIO	SEGF	☐	☐	☑	☐		
RC1	Pin Module	GPIO	SEGL1L2	☐	☐	☑	☐		
RC2	Pin Module	GPIO	SEGC	☐	☐	☑	☐		
RC3	Pin Module	GPIO	CDL1L2	☑	☐	☑	☐		
RC4	Pin Module	GPIO	SEGE	☐		☑	☐		
RC5	Pin Module	GPIO	CD3	☑		☑	☐		
RC6	Pin Module	GPIO	SEGD	☐	☐	☑	☐		
RC7	Pin Module	GPIO	CD2	☑	☐	☑	☐		

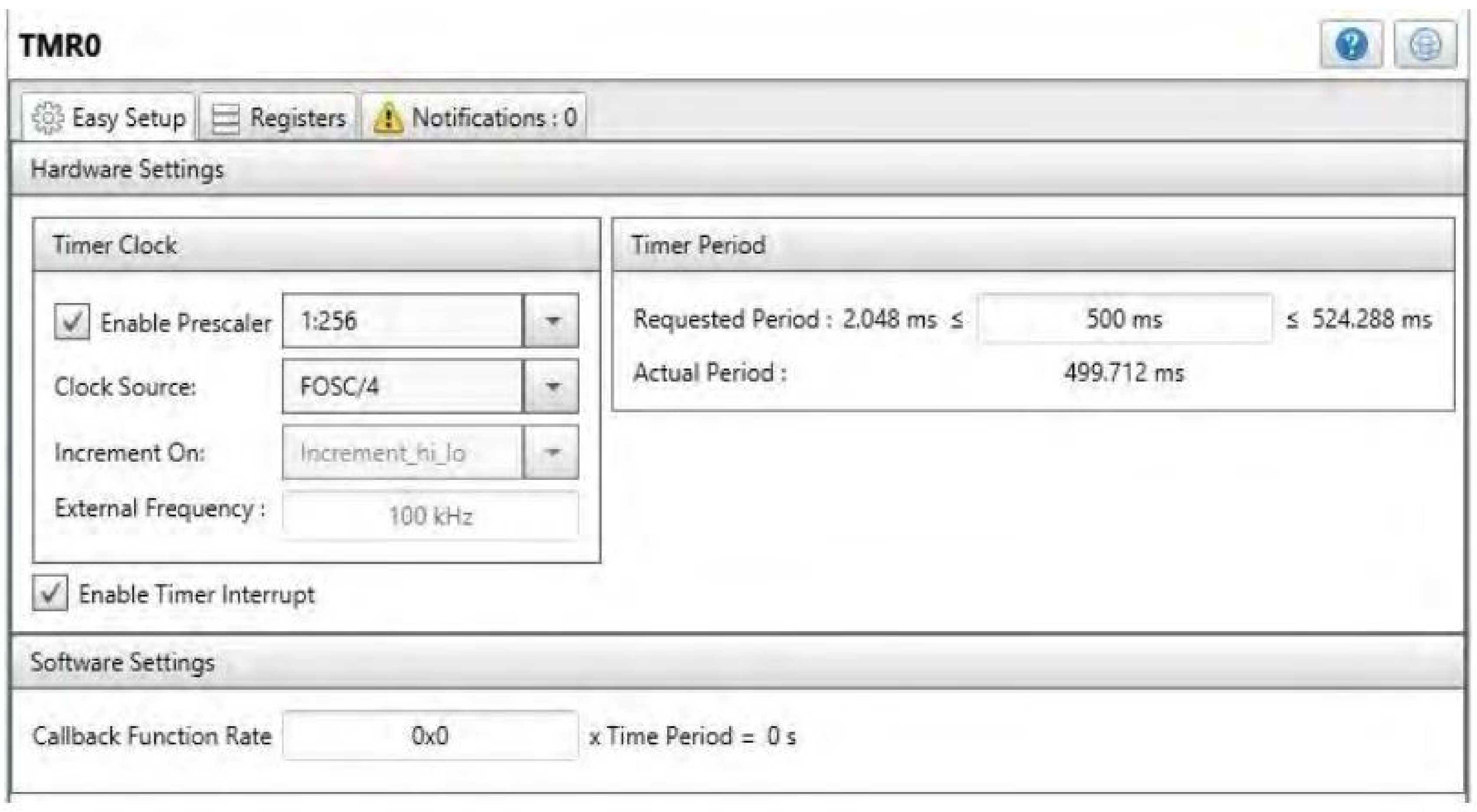
Package: PDIP20

Module	Function	Direction	Port A 0	Port A 1	Port A 2	Port A 3	Port A 4	Port A 5	Port B 4	Port B 5	Port B 6	Port B 7	Port C 0	Port C 1	Port C 2	Port C 3	Port C 4	Port C 5	Port C 6	Port C 7
Pin No:			19	18	17	4	3	2	13	12	11	10	16	15	14	7	6	5	8	9
OSC	CLKOUT	output					🔓													
Pin Module ▼	GPIO	input	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓
	GPIO	output	🔓	🔒	🔒	🔓	🔒	🔒	🔒	🔒	🔒	🔒	🔒	🔒	🔒	🔒	🔒	🔒	🔒	🔒
RESET	MCLR	input				🔒														
TMR0	T0CKI	input			🔓															

Fig.3. Microchip's Code Configurator Pin Module window

the third and fourth digit. It's important to note that each of the common-cathode outputs are set to 'Start High'. This ensures that the display is off at start up. In the Pin Manager panel at the bottom of Fig.3, we can see that nearly all of the GPIOs are used as outputs. RA0 and RA1 are actually the programming pins, but these can also be used as GPIOS during normal operation. RA3 is MCLR, notice how the input/output selection is greyed out here, so we don't accidentally set it as something else.

Once we click generate, all of these pins will be set up with their chosen names. MCC will also generate a number of easy-to-use functions that easily allow us to control and access each GPIO. Example functions include SEGA_SetHigh(), SEGA_SetLow(), SEGA_Toggle(), SEGA_GetValue() and a few more. SEGA_SetHigh() is far easier to understand than it's C counterpart: LATBbits.LATB4 = 1;



Hardware Settings

Timer Clock

☑ Enable Prescaler: 1:256

Clock Source: FOSC/4

Increment On: Increment_hi_lo

External Frequency : 100 kHz

Timer Period

Requested Period : 2.048 ms ≤ 500 ms ≤ 524.288 ms

Actual Period : 499.712 ms

☑ Enable Timer Interrupt

Software Settings

Callback Function Rate 0x0 x Time Period = 0 s

Fig.4. Microchip's Code Configurator TMR0 configuration window

Setting up the Timer

We looked at setting up a timer in previous articles – it involves some maths and careful set up of the registers to get it working accurately. MCC makes this a whole lot easier. To add Timer0 to our project double click on Timer0 under Timer in the Device Resources window. This will add it to our peripherals under Project Resources. To keep our project relatively low power, our clock is set to 500kHz. This is done under System Module. This is the base clock that our Timer0 will be derived from.

Ideally, we would like some sort of interrupt, which occurs every second and increments the seconds variable. Fig.4 shows the TMR0 setup in MCC, where we find that with the maximum prescaler of 1:256 and FOSC/4, gives a maximum interrupt value of 524.288ms. To try and get an even number, we could select 500ms under the requested period. This gives us an actual period of 499.712ms. This is more accurate than I expected, and gives us a 0.05% accuracy, which works out as a lost second every 30 minutes. (Not bad, but as discussed previously, if we used a 32.786kHz external clock, we could significantly improve this accuracy.)

The code itself

MCC has done a lot of the tedious work, now it's time to take a look at adding the functionality.

```
#include "mcc_generated_files/mcc.h"
#include "functions.h"

volatile uint8_t seconds = 0;
volatile uint8_t half_second = 0;

void main(void) {
    uint8_t maxseconds = 60;
    seconds = 0;
    half_second = 0;

    SYSTEM_Initialize();
    INTERRUPT_balInterruptEnable();
    INTERRUPT_ralInterruptEnable();
    __delay_ms(100);

    while (1) {
        if(seconds >= maxseconds) {
            updateTime();
        }
        updateDigits();
    }
}
```

This is all the code in `main.c`. I'm a fan of keeping the main `while` loop very simple and moving all other functions into another C file, containing a number of functions we can use again and again. In this project I have grouped all the functions into `functions.c`. This also has a header file called `functions.h`, which is used to declare the functions that will be used.

Looking at the code in `main.c`, we start off by including the MCC generated files under `mcc.h`. Next, we include our own separate functions header under `functions.h`. `SYSTEM_Initialize()`, `INTERRUPT_GlobalInterruptEnable()` and `INTERRUPT_PeripheralInterruptEnable()` are all created by the MCC. Then we delay for 100ms. This isn't absolutely necessary, but from experience, I always add a delay at the start to allow the power supply voltage to settle.

The `while` loop is short and sweet. We check to see if the seconds count has exceeded `maxseconds` and update the time values if necessary. Then we display each digit using the `updateDigits()` function.

Here we have a new variable type that we haven't covered previously. The `volatile` type qualifier is used to tell the compiler that an object cannot be guaranteed to retain its value between successive accesses preventing optimisations on this variable, which can alter the behaviour of the program. Volatile types are used when variables are modified in interrupt routines. Both of the variables `seconds` and `half_second` are used in the `Timer0` interrupt, which we will see further on. In the main loop, we read the value seconds to see if it is greater than or equal to the `maxseconds` value. The `Timer0` interrupt would be considered outside the normal flow of the program. The error checks inside the PIC will notice that this variable is being modified outside of the normal flow and will throw an exception error – however, using the volatile type tells the compiler that this variable can be modified in this way.

```
uint8_t displayDigit(uint8_t digit, uint8_t number) {
    clearDigits ();
    displayNumber (number);
    CDL1L2_SetLow();

    switch(digit) {
        case 1: CD1_SetLow(); break;
        case 2: CD2_SetLow(); break;
        case 3: CD3_SetLow(); break;
        case 4: CD4_SetLow(); break;
        default: clearDigits(); break;
    }

    return 1;
}
```

Turning to optimisation, the compiler will see the comparison statement `if(seconds >= maxseconds)` and notice that the variable `seconds` is not modified anywhere else in the normal flow of the code. It will then decide that the code is superfluous and replace it with `if(false)` as this will always be the case. The volatile type qualifier tells the compiler not to optimise this and leave it alone.

```
uint8_t updateDigits(void) {
    displayDigit(digit1, digit1val);
    __delay_us(10);
    displayDigit(digit2, digit2val);
    __delay_us(10);
    displayDigit(digit3, digit3val);
    __delay_us(10);
    displayDigit(digit4, digit4val);
    __delay_us(10);

    return 1;
}
```

Let's look into `functions.c`, where we will store all our regular functions. The first is the code above for `updateDigits()`, which rotates between each digit, displaying the correct value using the function `displayDigit()` and then waiting for 10µs, before moving on to the next digit.

This next piece of code shows the breakdown of the `displayDigit()` function. The goal of this function is to select the digit to be displayed. This takes two variables as inputs, the first selects the digit to be shown and the second takes the number to be displayed. To prevent ghosting it is necessary to set each segment low before displaying the new number. This is done using the function `clearDigits()`. Next, we execute the function `displayNumber()`, which is described below.

We have a new statement in this function called `switch` which is a nicer alternative to numerous `if  else` statements. The `switch` statement takes a variable and compares it to the various cases. In the code above, if the digit variable is equal to 3, then `case 3` is selected and the `CD3_SetLow()` function is called. It's good practice to have a `default case` in the event the input variable is outside the bounds of all the cases. Note how each case ends with `break;`, this exits the `switch` statement loop. Without this, the `switch` statement will execute all further cases.

```
uint8_t displayNumber(uint8_t number) {
clrNumber();
SEGL1L2_SetHigh();

switch(number) {
    case 0:
        SEGA_SetHigh();
        SEGB_SetHigh();
        SEGC_SetHigh();
        SEGD_SetHigh();
        SEGE_SetHigh();
        SEGF_SetHigh();
        SEGG_SetLow();
        break;

        ...
```

It is not feasible to display all of the code, but a subset explaining the main points will suffice. The goal of this piece of code is to display the correct number on the selected digit. This code (above) shows the display of just one value, 0. The function `displayNumber()` is called inside `displayDigit()`. First, it is important to clear all segments using the `clrNumber()` function, which simply sets all segments to low, turning them off. Next, we turn on the semicolon using `SEGL1L2High()`. An interesting note here is that we could leave the semicolon on the whole time, but this would leave it much brighter than the surrounding digits. This method both reduces power consumption and the obvious difference in brightness.

In `displayNumber()` above, we see the switch statement again. This time it takes the variable number. In case 0, we want to display the number 0. Looking back at Fig.1, we see that we need to illuminate segments a, b, c, d, e and f, while 'g' is set low. Using the MCC pre-configured functions, we can set each segment using the names we gave them earlier.

```
uint8_t updateTime(void) {



    minutes++;
    seconds = 0;

    if(minutes >= maxminutes) {
        tenminutes++;
        minutes = 0;
    }
    if(tenminutes >= maxtenminutes) {
        hours++;
        tenminutes = 0;
        minutes = 0;
    }
    if(hours >= maxhours) {
        tenhours++;
        hours = 0;
        tenminutes = 0;
        minutes = 0;
    }
    if(((tenhours >= 2) && (hours >= 4)) || (tenhours > 2)) {
        tenhours = 0;
        hours = 0;
        tenminutes = 0;
        minutes = 0;
    }

    digit4val = minutes;
    digit3val = tenminutes;
    digit2val = hours;
    digit1val = tenhours;
}
```

The last function is the `updateTime()` function. This is executed every minute, once the `seconds` variable in the main while loop exceeds `maxseconds (60)`. This function was discussed earlier when we talked about splitting up the separate digits on the display and when to increment each one. Fig.2 demonstrates this function after the `seconds` variable is greater than 59 seconds.

Notice how the variables used in this function are separated from the variables passed into the `updateDigits()` function. `Minutes`, `tenminutes`, `hours` and `tenhours` are manipulated first before storing them in `digit4val`, `digit3val`, `digit2val` and `digit1val`. This is good practice and ensures all value modifications are made before storing them in the used values.

```
void TMR0_ISR(void) {
    INTCONbits.TMR0IF = 0;
    TMR0 = timer0ReloadVal;

    if(half_second) {
        seconds++;
        half_second = 0;
    } else {
        half_second = 1;
    }

    if(TMR0_InterruptHandler) {
        TMR0_InterruptHandler();
    }
}
```

The MCC has already setup the interrupt for `Timer0`. At the moment, `Timer0` will interrupt every 500ms and reset the interrupt. We need to add a small bit of code to the interrupt in `tmr0.c`. The code above shows the additional `if else` statement, which toggles the `half_second` variable, and every time it is equal to 1 it will increment the `seconds` variable. This makes sure the `seconds` variable is incremented every second. These are the two volatile variables we discussed earlier.

One thing to note in the code is that our focus is on continually rotating the display of each digit. In the main code, we only check to see if `seconds` has exceeded `maxseconds` before continuing back into the rotation. Any added delays between the display in each digit will cause flicker in the display. The complete code can be downloaded from the *EPE* website. Fig.5 shows the finished project with the time displayed.

Next month

In *Part 3* next month we will look at a 4 × 4 keypad and see how we can attach it up to our display to create a basic calculator. We've used up all our GPIO pins, so it should be interesting to see how to do this.

Not all of Mike's technology tinkering and discussion makes it to print.

You can follow the rest of it on Twitter at *@MikePOKeeffe*,

and from his blog at *mikepokeeffe.blogspot.com*

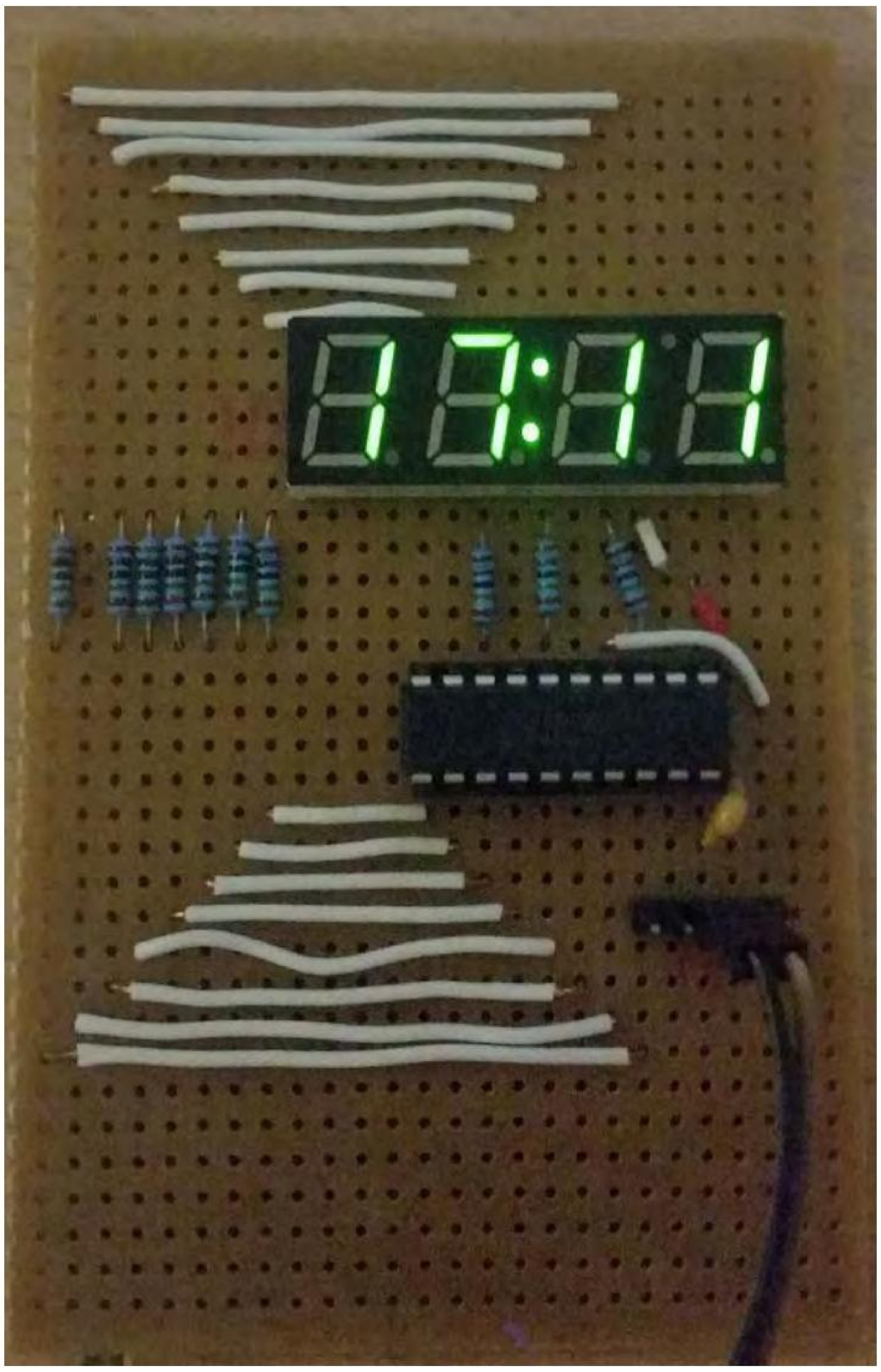


Fig.5. Completed 24-hour Clock using a four-digit, seven-segment display

CIRCUIT SURGERY

REGULAR CLINIC

BY IAN BELL

Temperature sensors – Part 4

THIS IS the fourth and final part of this *Circuit Surgery* series on temperature sensors and their associated circuits, which was inspired by a letter to *EPE* from Ewan Cameron (August 2017) suggesting topics of interest related to PIC microcontrollers, including accurate temperature sensing. So far, we have looked at temperature measurement circuits using self-contained analogue and digital temperature sensor ICs, and at temperature measurement using thermocouples. This month, we will look at resistance-based sensors – thermistors and resistance temperature detectors (RTDs).

Keep sending me ideas!

Before getting started I would like to mention the new *EPE* discussion forum on EEWeb (**eeweb.com/forum** with the 'epe-magazine' tag). Regular readers will know that many *Circuit Surgery* articles have been written in response to questions on the now-retired *EPE Chat Zone* (for full details see this month's and recent *Net Work* columns). I hope and expect to be able to continue using reader's forum posts as the inspiration for these articles – after all, that is origin of this feature, back to pre-Internet days when the authors at the time received sacks full of handwritten letters. I encourage you to check out the new forum, but of course you can still contact *EPE* directly with a question or topic suggestion for *Circuit Surgery*.

Resistance-based temperature measurement

Many physical properties of materials vary with temperature, and if we want an electronic temperature sensor then the variation of electrical conductivity of materials is perhaps an obvious choice. We refer to 'conductivity' here, rather than 'resistance', because it is the fundamental property of the material rather than that of an individual device. A resistor has fixed physical geometry and will have a fixed resistance if the electrical conductivity of the material from which it is made does not vary for any reason. However, if we make another resistor from the same material, but with a different shape, its resistance is likely to be different from that of the first device. Once we have constructed a resistor, its resistance will vary if the electrical conductivity of its material changes with temperature. The degree to which the resistance of a resistor changes with temperature is called its temperature coefficient of resistance. Temperature coefficients may be negative or positive, that is the resistance may either increase or decrease with increasing temperature, depending on the material. Thermistors are available with both positive and negative temperature coefficients – designated PTC and NTC devices respectively. The NTC types tend to be used more frequently in temperature measurement, while the PTC types are often employed in applications such as over-current protection. RTDs have a positive temperature coefficient.

In simple terms, if you are making a fixed resister you want the coefficient to be as low as possible so its value does not change with the operating temperature of a circuit. On the other hand, if you want a temperature sensor you probably want a large temperature coefficient. However, this is not the whole story because temperature coefficients also change with temperature, meaning that the resistance change with temperature is nonlinear. This leads to a key difference between NTC thermistors and RTDs. NTCs show a large but very nonlinear variation of resistance with temperature, whereas RTDs have much lower temperature coefficient but are much more linear. The materials employed to make the devices determine these behaviours. Thermistors used for temperature measurement are made using semiconducting materials, usually oxides of chromium, manganese, iron, cobalt or nickel. RTDs are made from conductors (metals), in particular platinum, which, despite its cost, has a number of advantages over other materials. It has a very linear and repeatable resistance relationship with temperature over a wide range of temperatures and is chemically inert. The resistance variation of platinum is well characterised and is used for calibration purposes, as defined by the international standard ITS-90.

RTDs and thermistors

The difference between the resistance *vs* temperature characteristics of NTC thermistors and RTDs is illustrated in Fig.1, which shows (approximately) the responses of a typical device of each type. NTC thermistors are usually specified in terms of their resistance at 25°C – there is a very large range of values readily available, from around 20Ω to 1MΩ. Values in the range 1kΩ to 100kΩ are the most commonly used. The thermistor show on the graph has a resistance of 1kΩ at 25°C.

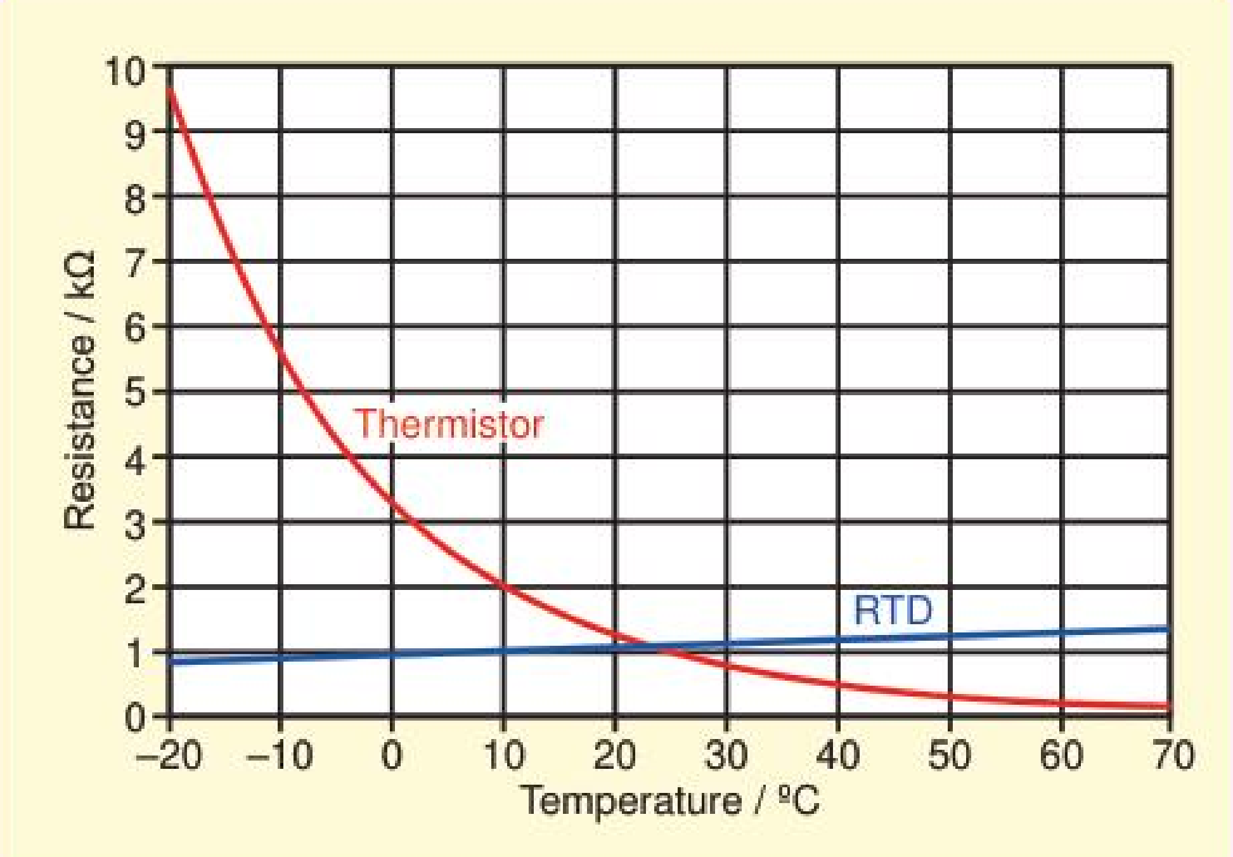


Fig.1. Comparison of approximate characteristics curves for typical NTC thermistor and RTD (PT1000).

Platinum RTDs

RTDs are specified in terms of their resistance at 0°C. There are far fewer values available, with by far the most common being devices made from platinum with resistances of 100Ω or 1kΩ at 0°C. These are designated PT100 and PT1000 respectively (Pt is the chemical symbol for platinum). The graph shows the resistance of a PT1000 sensor. Other values such as PT200 (200Ω) and PT500 (500Ω) are available, however the range of values is far smaller than for NTC thermistors.

The small number of RTD values available might seem like a disadvantage, indicating lack of choice, but in fact it is an advantage over other temperature sensor types in that their responses are standardised; this makes it easier to swap sensors in a system and get the same response. PTx RTDs are only really used in measurement applications, whereas NTC thermistors have a wider range of applications (for example temperature compensation of transistor bias and inrush current limiting), for which a larger range of values is useful. Both NTC thermistors and RTDs are available in a range of physical package types and formats to suit applications in different situations.

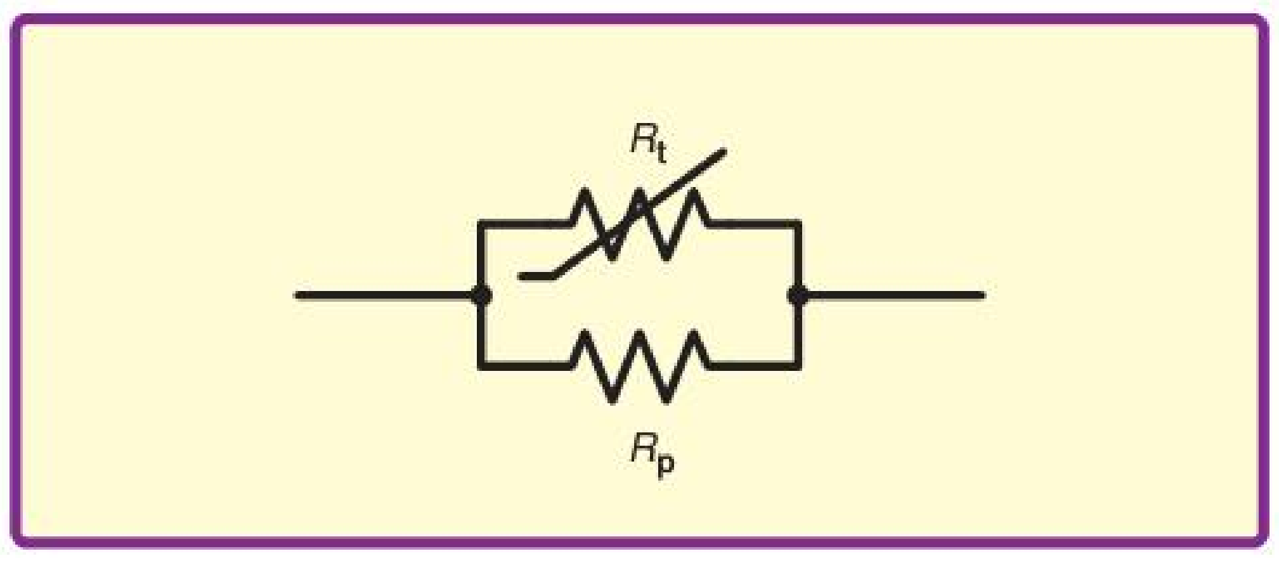


Fig.2. Parallel combination of resister and thermistor

Thermistor non-linear response

The nonlinear variation of resistance of NTC thermistors presents a potential problem when using them for temperature measurement, particularly if a wide measurement range is required. The resistance-temperature characteristic can be linearised to some extent by connecting a resistor in parallel with the thermistor, as shown in Fig.2. The resistor should be selected to match the resistance of the thermistor at the mid-point of the required measurement range.

Here's an example of linearisation – consider a thermistor with the characteristic curve shown in Fig.1, and a measurement mid-point of 25 °C – a 1kΩ parallel resistor would be suitable. The resulting resistance-temperature characteristic of this combination is shown (approximately) in Fig.3, together with the original thermistor characteristic and that of the resistor, which is assumed not to vary with the temperature being measured. Using a thermistor with a parallel resistor improves linearity over a limited temperature range but also reduces sensitivity – the graph shows that the parallel combination exhibits much less temperature variation than the thermistor alone.

To measure a resistance, some current must be passed through the resistance. A simply way to achieve this is to use a potential divider, as shown in Fig.4 – an excitation voltage (V_{excite}) provides the current flow to facilitate measurement. The output voltage (V_{temp}) in the circuit shown will increase with increasing temperature. Swapping the position of the resistor and thermistor will result in the opposite trend. This circuit also has a linearising effect on the response in comparison with the thermistor's resistance-temperature characteristic. Just like the parallel circuit, the divider resistor (R_d) should be chosen to match the thermistor's value at the mid-point of the measurement range. The output voltage of the thermistor potential divider can be input directly to an on-chip ADC in a microcontroller to make a simple measurement system. An amplifier could also buffer it.

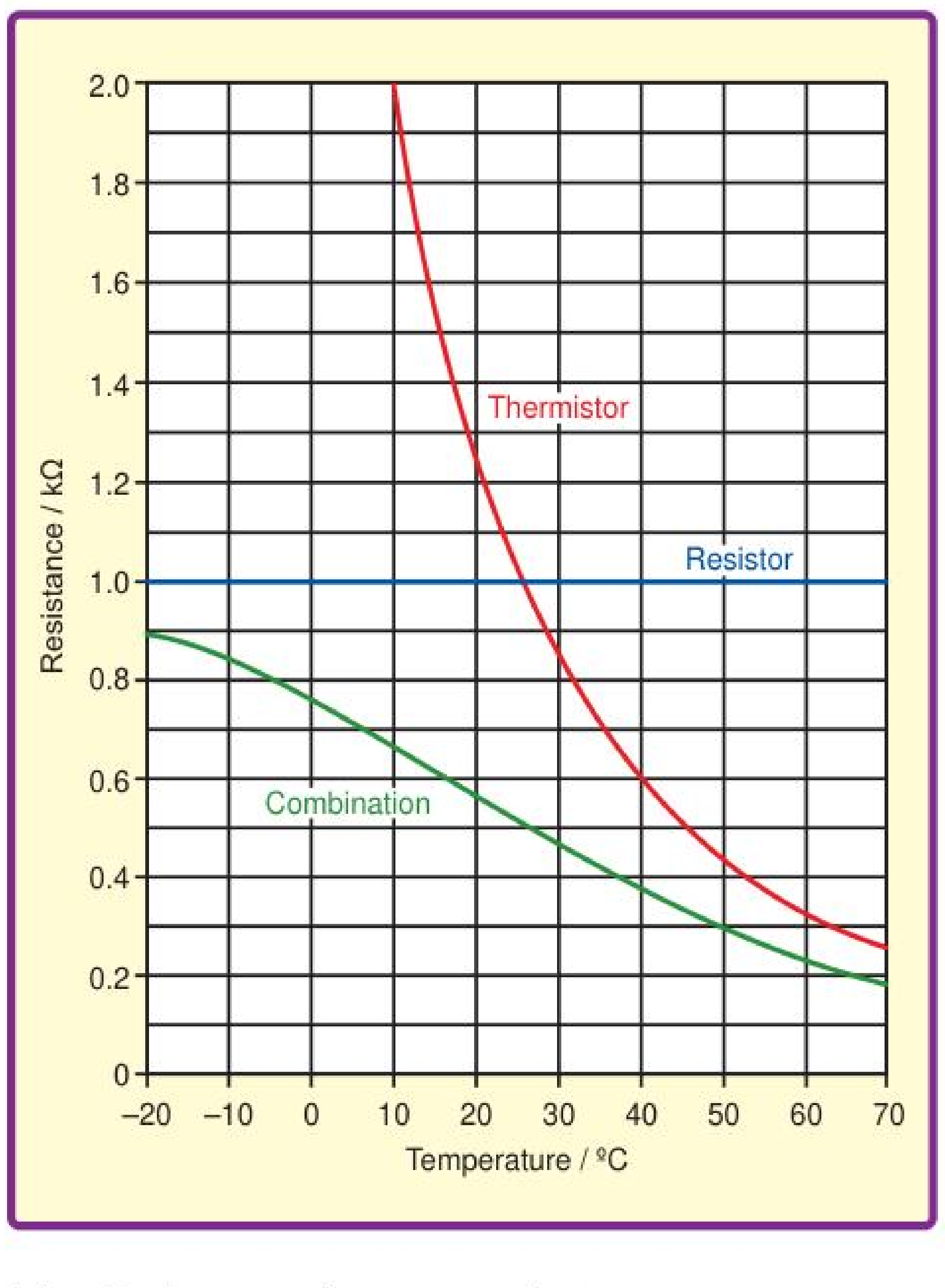


Fig.3. Approximate resistance-temperature curves for a 1kΩ-at-25°C thermistor in parallel combination with 1kΩ resistor. The original thermistor and resistor characteristics are also shown.

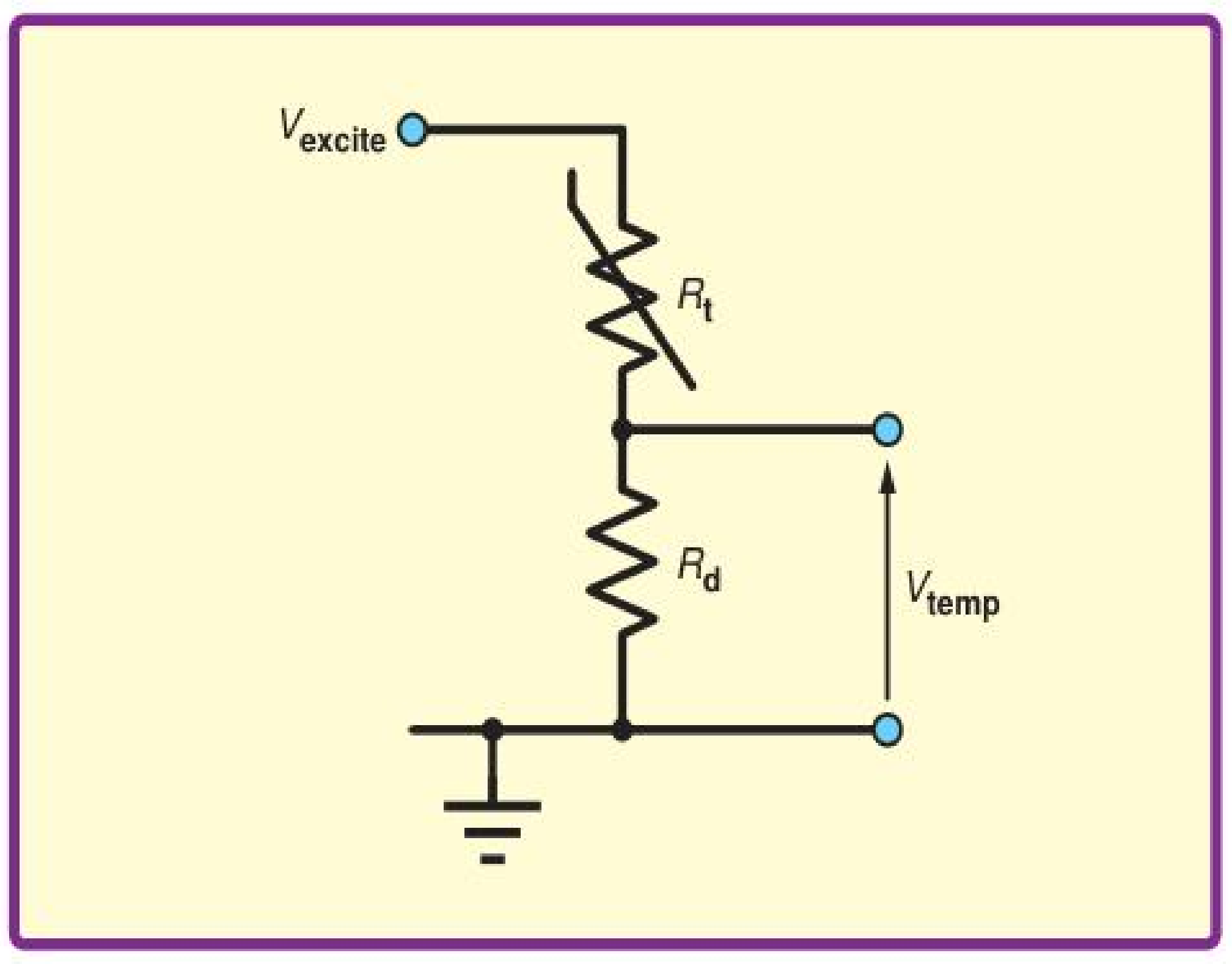


Fig.4. Thermistor potential divider circuit

More complex combinations of resistors can be used to improve linearity further, for example using a potential divider with additional resistors both in parallel and series with the thermistor, although this will further reduce sensitivity. Such linearisation may be unnecessary, particularly at the expense of sensitivity, if the measurement is to be made by a microcontroller which can perform the linearisation in software.

If a single potential divider is used with a sensor that exhibits small resistance changes it will produce an output voltage that only varies over a small range on top of a large offset. This can be difficult to use (eg, when digitising to high resolution). The differential voltage from a bridge (see Fig.5) does not have this offset, so can be amplified (by a suitable differential amplifier) without the offset causing the amplifier to saturate. Bridges are most needed when sensor resistance variation is small, so may not always be necessary with thermistors.

Bridge circuits

If a bridge is used, R_1 (in Fig.5) will typically match the thermistor's resistor in the middle of the temperature range. R_2 and R_3 could have the same value, in which case the output voltage will be zero at mid-range, although different values can be used for a particular output voltage at a given temperature. Note that the amplifier in Fig.5 is a differential amplifier, or an instrumentation amplifier, with good common-mode rejection and a suitable internally set gain. It is *not* an open-loop operational amplifier. If a bridge circuit is used with an ADC then the excitation voltage can be used as the ADC's reference voltage. This will compensate for any variation in excitation voltage. Alternatively, the excitation voltage can also be measured and compensation performed in software.

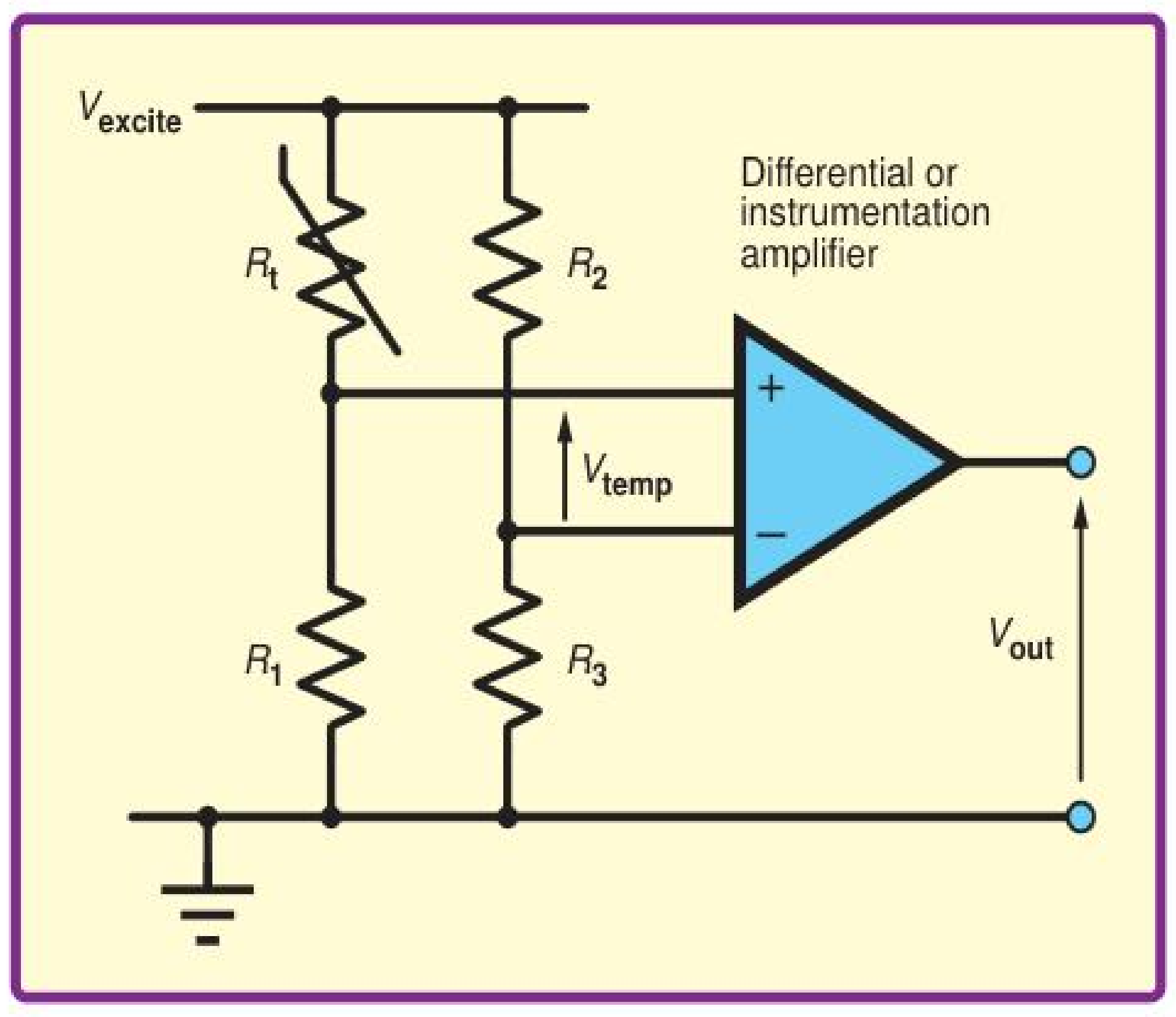


Fig.5. Thermistor bridge circuit

Current issues

With any resistance-based temperature measurement (thermistor or RTD) some care is needed with the amount of excitation current passed through the sensor to make the measurement. Any current (I) flowing in a resistance (R) dissipates power (equal to I^2R) and potentially causes a change in temperature of the device – an effect known as self-heating. In the context of Fig.4 and 5, a low excitation voltage will reduce this effect but also reduce the signal level. In some thermistor applications self-heating is used deliberately to sense the thermal conductivity of the environment of the sensor – for example, if a liquid is present it will remove heat from the sensor to a much greater extent than air, so the liquid can be detected by a temperature change. In direct temperature measurement self-heating is of course a problem and will cause inaccuracies in the measurement if it occurs.

Software compensation

As previously mentioned, sensor non-linearity can be compensated for in software. A basic approach is to use a look-up table. The table is in effect a set of points on a graph that maps from the ADC reading to the temperature. The more points (table entries) used the more accurate the results can be, but more memory will be needed. If the ADC reading is between points on the table then interpolation is required – the simplest approach is to assume the characteristic is a straight line between the points. An alternative to using a table is to obtain a polynomial equation to fit the characteristic curve of the measurement response. The polynomial is an equation of the form:

$$\text{Temperature} = a + bx + cx^2 + dx^3 + \ldots$$

Here, x is the measurement response (from the ADC) and a, b, c… are the called the 'coefficients'. The more powers of x the equation includes the more (potentially) accurate the compensation – but more processing effort is required. If temperature *vs* measurement data is available then various mathematical software tools can be used to obtain the coefficients.

Finally, for thermistors, measurement software may make use of a specific model of resistance-temperature variation of semiconductors called the Steinhart-Hart equation. The full equation has four parameters (A, B, C, D) which vary for each type of device, and with temperature range, and may be available from the device manufacturer. There is a simplified version of the equation called the B or β equation, which uses a parameter called β (beta) and the resistance of the thermistor at known temperatures. More specifically, because the β parameter varies it is usually specified between two temperatures (eg, 25°C and 85°C, in which case it is denoted $B_{25/85}$). B (or beta) is defined using the following equation:

$$B_{T_1/T_2} = \frac{\ln\left(R_1 / R_2\right)}{\left(\frac{1}{T_1} - \frac{1}{T_2}\right)}$$

Where R_1 is the resistance at T_1 and R_2 is the resistance at T_2, with temperatures in kelvin. Knowing B, and the resistance R_0 at temperature T_0 (usually 25°C), the temperature (T) can be found from the resistance (R_T) measured at that temperature using:

$$T = \frac{\dfrac{T_0 B}{\ln\left(\dfrac{R_0}{R_T}\right)}}{\dfrac{B}{\ln\left(\dfrac{R_0}{R_T}\right)} - T_0}$$

Thermistor datasheets also specify a parameter called 'alpha' (α) at various temperatures. The α term is the temperature coefficient of resistance, so given a temperature change of ΔT from the temperature at which α is specified and the resistance (R) at the specified temperature the change in resistance is:

$$\Delta R = \alpha R \Delta T$$

α is of course negative for NTC thermistors.

RTDs are much more linear than thermistors, but for highly accurate measurements they also need to be linearised in software using similar techniques. As with thermistors, there is a named equation – the Callendar-Van Dusen equation – which can be used. However, greater accuracy can be obtained with high-order polynomial curve-fitting, at the expense of more computational effort. Platinum RTDs have the advantage over thermistors of standardisation of the equation parameters (for devices to meet the relevant international standards for PT100 etc.).

RTDs (eg, PT100 or PT1000) can be used in the potential divider and bridge circuits described above, but the small variation of resistance with temperature leads to potential problems with the resistance of the wires (lead resistance R_L) used to connect the RTD to the measurement circuit. The resistances are unknown and variable and may be of a similar magnitude to the resistance variation of the RTD with temperature. The lead resistance can potentially therefore produce significant errors and undermine the RTD's potential for highly accurate temperature measurement.

Lead resistance

To overcome the problem of lead resistance, RTDs are usually used in a three-wire or four-wire measurement circuit (see Fig.6 and 7). The principle of this approach is to generate a constant current and pass it through the device to create a voltage drop which is dependent on its resistance and hence the temperature. A three-wire system can also be used with a bridge circuit.

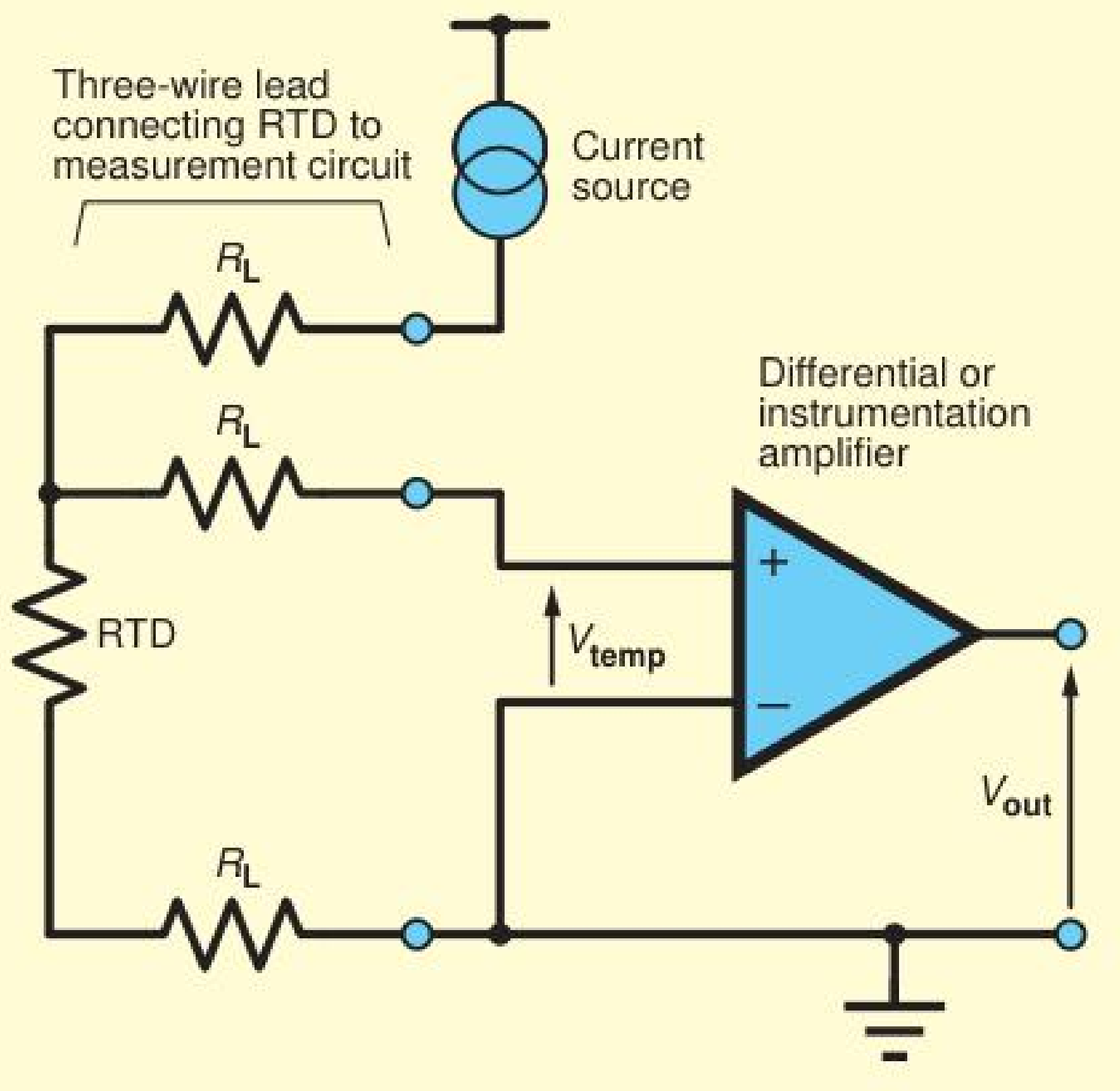

Three-wire lead connecting RTD to measurement circuit
Current source
R_L
R_L
Differential or instrumentation amplifier
RTD
+
V_{temp}
–
V_{out}
R_L

Fig.6. Three-wire RTD measurement circuit

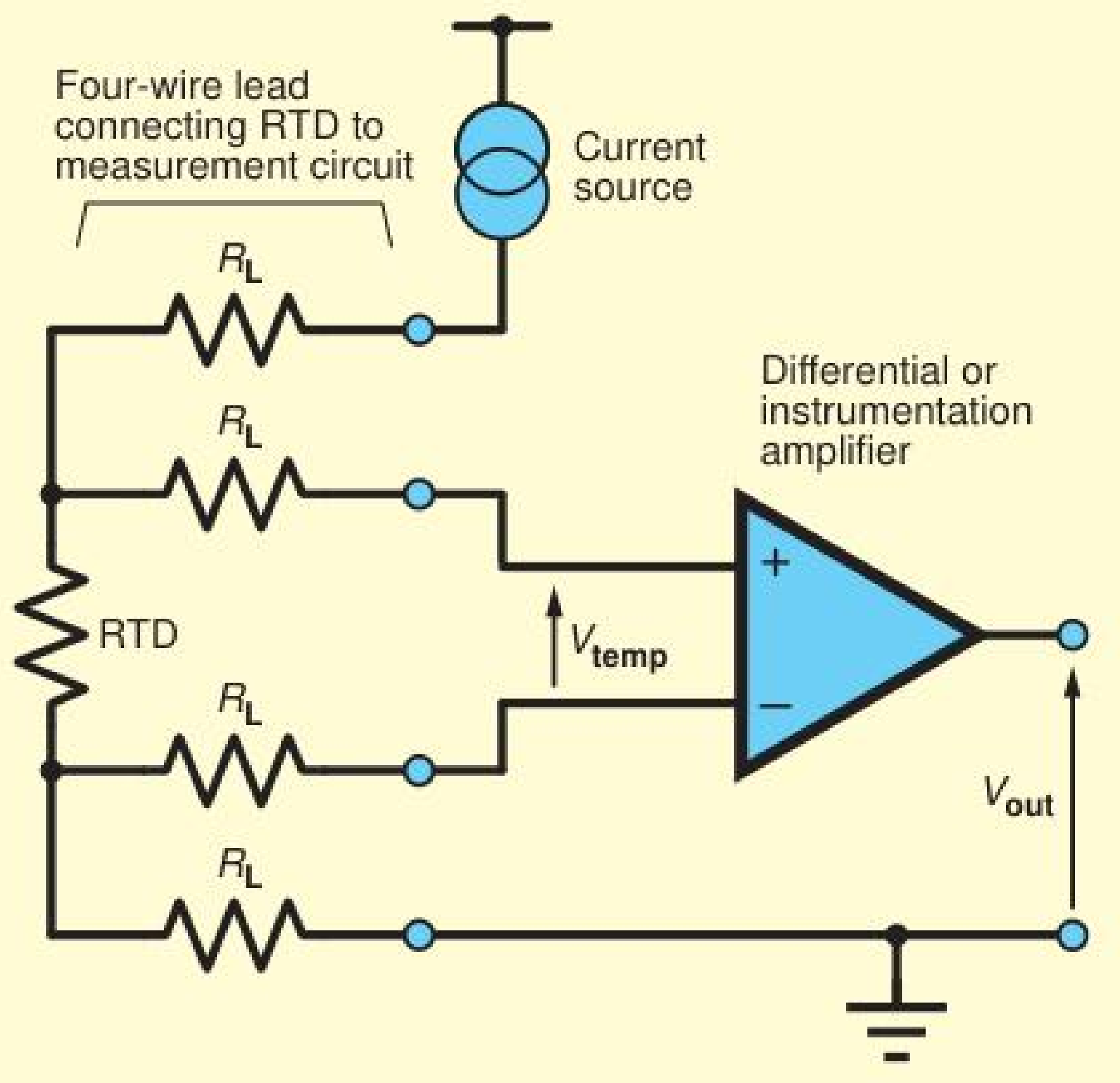

Four-wire lead connecting RTD to measurement circuit
Current source
R_L
R_L
Differential or instrumentation amplifier
RTD
+
V_{temp}
R_L
–
V_{out}
R_L

Fig.7. Four-wire RTD measurement circuit

In the circuits in Fig.6 and 7 the voltage across the RTD is measured via separate wires connected directly across the sensor, using an amplifier with high input impedance and very low input bias current. This means that very little current flows in the measurement wires so that very little voltage is dropped across their resistance. A much larger voltage can be dropped across the wires supplying the excitation current because these drops are not (all) included in the measured voltage. The four-wire circuit bypasses the drop in both wires so is more accurate than the three wire approach, but requires more wiring. A three-wire arrangement that switches the current source through just two of the wires can also be used – the wire resistance is measured this way and subtracted from the RTD plus R_L measurement. The current source can be connected to ground or supply and can be provided by a current source IC such as the REF200 from Texas Instruments.

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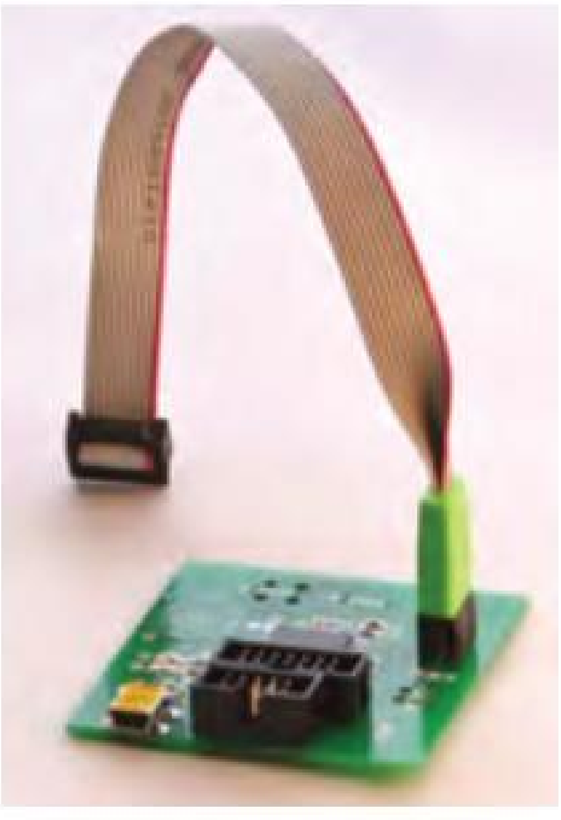

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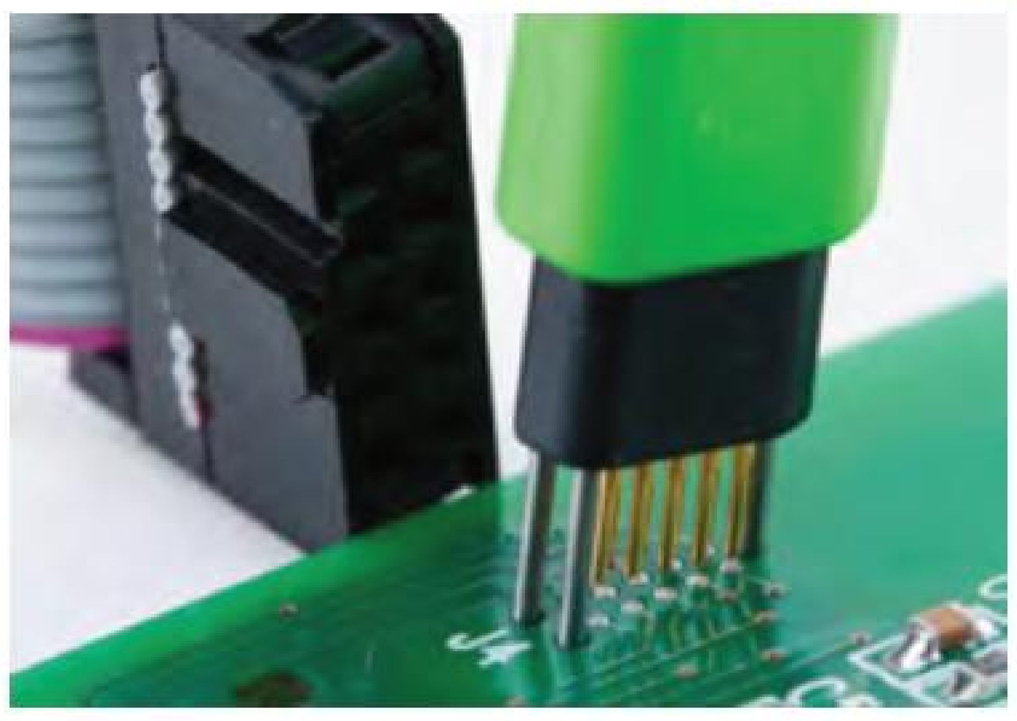

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Max's Cool Beans

By Max the Magnificent!

If it's Friday, it must be Sheffield

I'm 'all of a fluster' at the moment. As I pen these words, I'm sitting in a hotel in Munich. Soon, I'm scheduled to start a series of meetings with a number of high-tech companies. In a couple of days' time I will be flying to London to attend some more meetings, after which I'll catch a train up to Sheffield to visit my dear old mum. Next, I head out to Denmark to give the keynote presentation at the Electronics of Tomorrow (EOT) conference, then back to the US in time to speak at the Embedded Systems Conference (ESC) in Minneapolis. Phew!

In addition to all this travelling, my head is spinning with myriad other things that are going on in my life, including my *Countdown Clock* project (see *EPE* Nov 2017) and the hardware control panel I'm using to fine-tune its effects (see last month's *Cool Beans*), but first…

Bertie the Brain

I never cease to be amazed by the ingenuity of the engineers of yesteryear. I've just been introduced to a miniature vacuum tube called an Additron (**http://bit.ly/2zymiPv**). Designed by Canadian engineer, Dr Josef Kates, the Additron implemented a full one-bit binary adder.

It was showcased in an early computer game called *Bertie the Brain* (**http://bit.ly/2gqN5WJ**), which was presented to the public at the Canadian National Exhibition (CNE) in 1950. The Additron had the potential to change the face of computing, reducing size and power consumption while increasing performance and reliability. However, the invention of the transistor and IC meant that the little Additron never really saw the light of day.

Who's in control?

In my previous column we discussed the creation of a hardware control panel. This little rascal boasts a single-pole, thirteen-throw rotary switch, three toggle switches, three momentary pushbutton switches, and five potentiometers. The idea is to use this control panel to fine-tune the various effects generated by my countdown timer.

If you wish, you can peek at the Arduino sketch (program) I wrote to make sure the control panel was working as expected (**http://bit.ly/2xZVn2N**). Perhaps the most interesting function is the one used to read and process the five potentiometers, which we can call A, B, C, D and E.

One of the problems with reading analogue inputs is noise, which can make subsequent readings wander up and down a bit. One way to address this is to take multiple readings and average them. How many readings? Well, that's application dependent. For my purposes, I decided to take eight samples from each input.

Why eight as opposed to, say ten, for example? Well, I come from a time where every clock cycle counted. If your number of samples is a factor of two, then performing the division that averages the result can be achieved using a simple shift operation (the compiler works this out for itself).

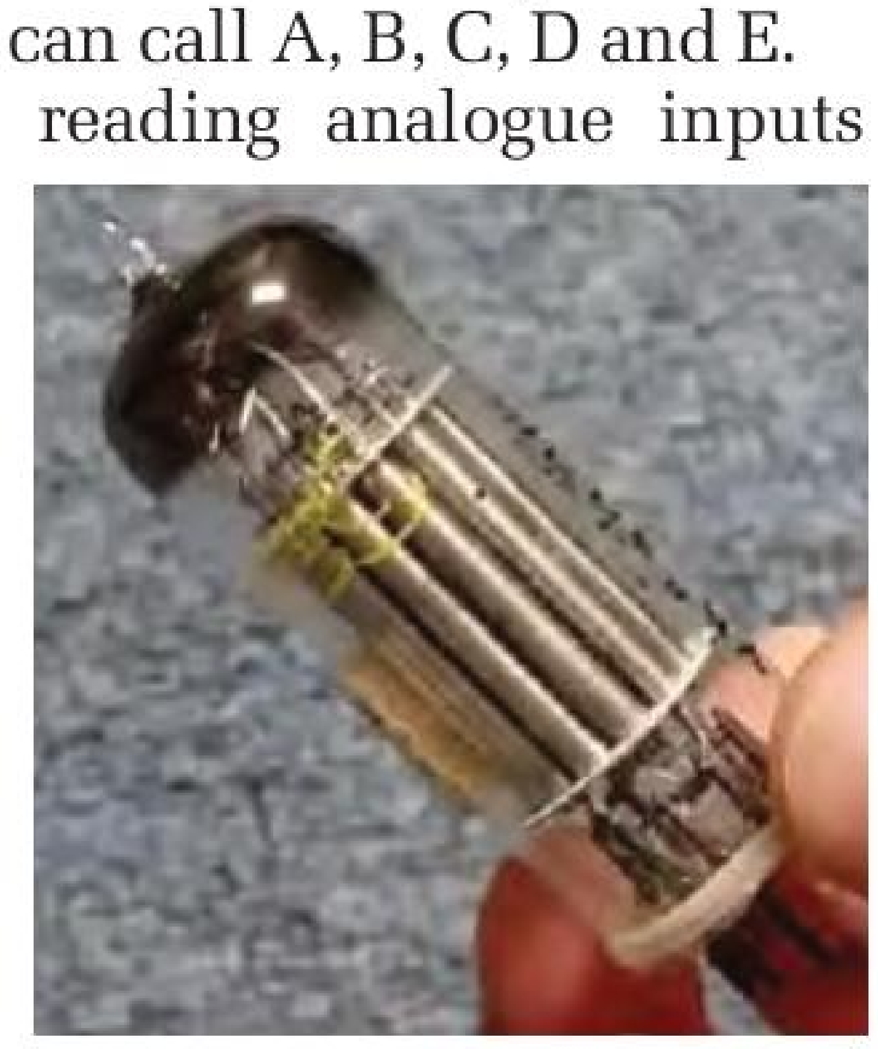

Fig.1. The remarkable Additron tube

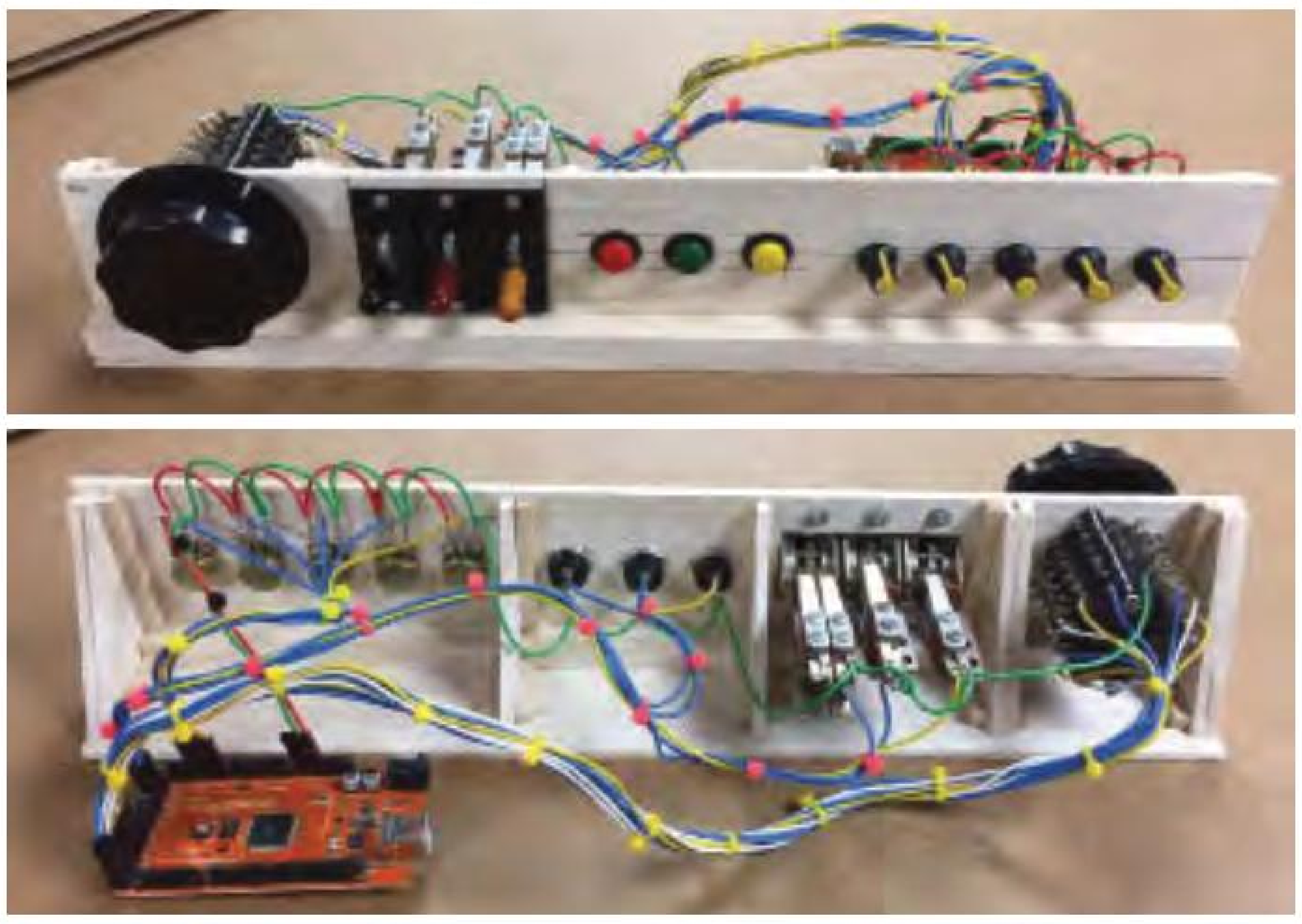

Fig.2. My awesome control panel – front and back

In a further attempt to minimise noise effects, I right-shift the 0-to-1023 result by two bits (>>2), which is equivalent to a divide-by-four. This means I throw the two least-significant bits (LSBs) away.

I also add 1µF ceramic capacitors between the signal wires (the potentiometers' wipers) and ground (0V) at the potentiometer end, and more 1µF capacitors between the signal wires and +5V at the Arduino end.

Last but not least, instead of sampling each input multiple times before moving on to the next (AAAAAAAA, BBBBBBBB, CCCCCCCC…), I sample each one in turn and repeat the process eight times (ABCDE, ABCDE, ABCDE…). The idea is to let any transient noise on a particular input die away before the next sample.

It's for you!

Regarding my *Countdown Clock*, I'd originally decided to use the rotary dial mechanism from a 1950s phone to enter the target date and time. But then someone suggested using an entire phone. Oooh! I can imagine picking up the phone and hearing a voice asking, 'What do you want?'

Then I can imagine saying, 'It's the Supreme Commander here, I want to enter a new date.' The voice would respond, 'Go ahead Supreme Commander,' after which I would use the rotary dial to enter the date.

Strange as it may seem, the voice recognition and synthesis will probably be the easiest part of all this. Somewhere under all the papers on my desk I have a MOVI shield (**http://bit.ly/2yM1jLO**) for the Arduino that will do all the heavy lifting for me. As soon as I return from my travels I will start experimenting, and I shall report further in a future column. Until then, have a good one!

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AUDIO OUT

By Jake Rothman

Railing against convention – Part 1

Introduction

Which is best, single or dual-rail amplifier powering? A simple question, but it's not simple to answer – there are many pros and cons. Discrete circuits are often single-rail powered (Fig.1a) which need output capacitors to block the half-rail DC bias. IC-based and symmetrical circuits lend themselves to dual-rail and, with a few exceptions, these don't need output capacitors. Today, most Hi-Fi systems are dual-rail (Fig.1b). In the past, single-rail systems dominated, but recently there has been a resurgence of single-rail topologies with the proliferation of battery-powered devices.

In this article I will look at both approaches. This issue was highlighted for me because I recently designed a synthesiser circuit, the Gen X-1, running on a 5V regulated single-rail derived from a 6V battery. For low-cost products like the Gen X-1, people expect to be able to run the device from a pack of 4 AA batteries. However, dual-rail battery supplies are a bad idea because individual cells don't go flat at the same rate. On the other hand, music synthesisers and effects pedals often use modulation frequencies down to 0.01Hz and so, using a dual-rail topology simplifies the design, avoiding huge-value coupling capacitors. I got round this problem by using a TL431 regulator which generated a centre-rail/artificial ground to effectively provide a ±2.5V supply (Fig.2).

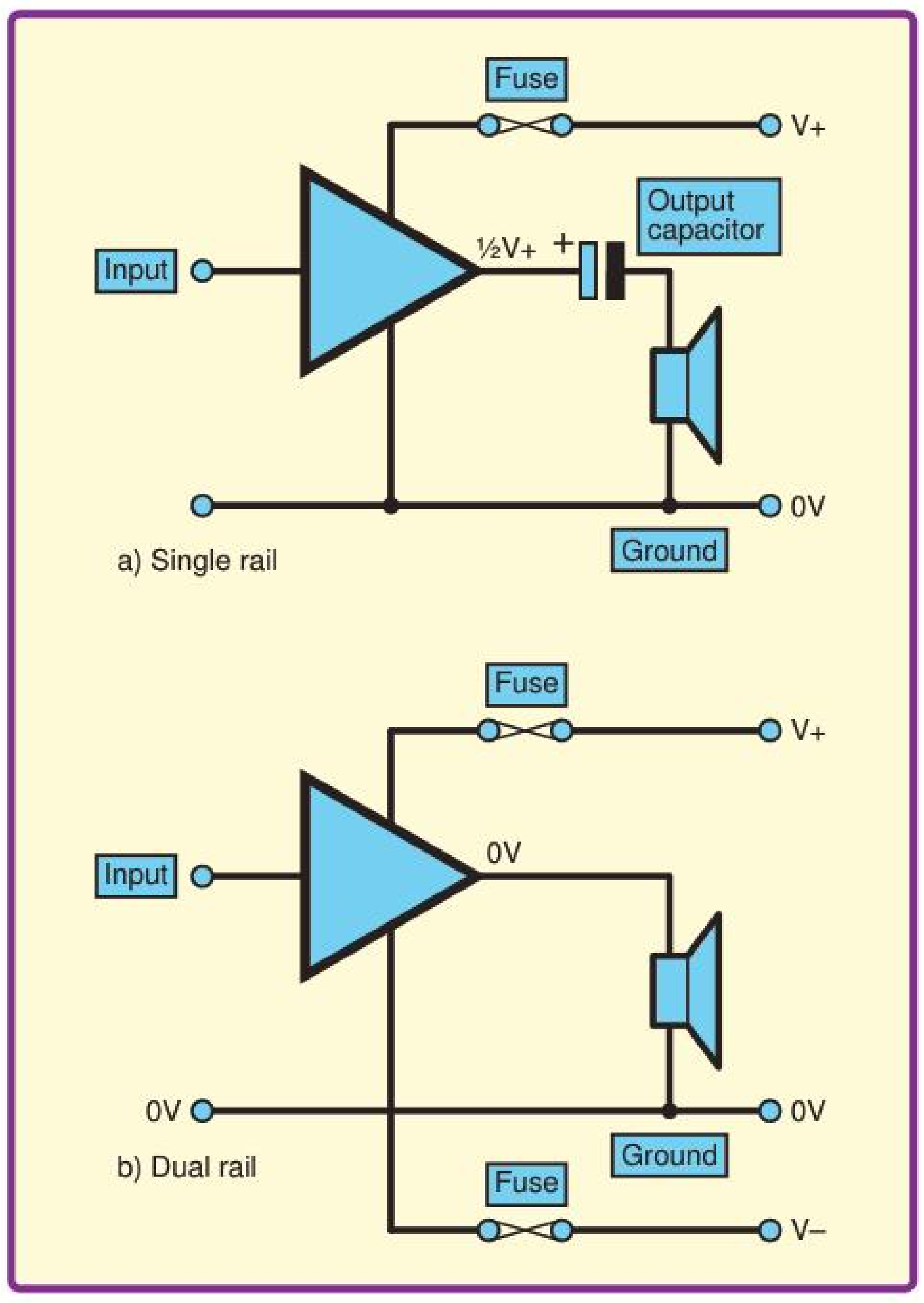
Fuse
V+
Output capacitor
½V+
+
Input
0V
Ground
a) Single rail
Fuse
V+
Input
0V
0V
0V
Ground
b) Dual rail
Fuse
V–

Fig.1. Amplifiers are generally single (a) or dual rail (b).

There are many conflicting engineering decisions that need to be considered when developing audio power supplies. In general, there are also output capacitor problems with single-rail systems, which we will address. Later we'll pull the ideas together to make a single-rail power amplifier based on the MX50 which was described last month.

The singularity

One simple advantage of single-rail design is that a standard bought-in power supply unit (PSU) or a vehicle supply is easy to use. (Dual-rail 'wall-warts' are rare.) Also, a single-rail stereo system can use a standard *twin*-winding toroidal transformer, allowing complete isolation between the two channels and thereby avoiding the possibility of earth loops. If isolation is required for a dual-rail design, a specially wound transformer is needed with a *pair* of centre-tapped secondary windings.

Ground currents

The main benefit of dual-rail design is that the ground rail is kept free of operating currents, making layout and wiring less critical. With single-rail circuits, the signal ground can become

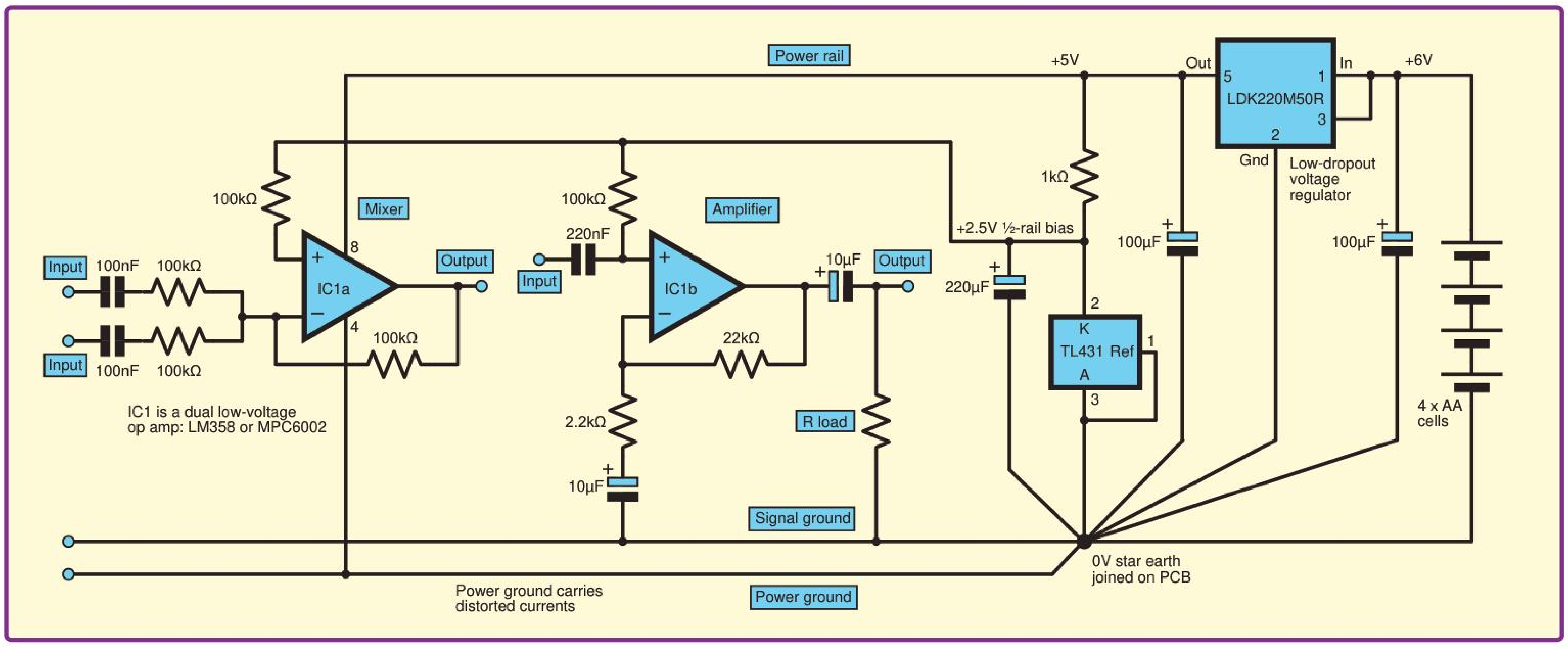
Power rail
+5V
Out
5
1
In
+6V
LDK220M50R
3
2
Gnd
Low-dropout voltage regulator
100kΩ
Mixer
100kΩ
Amplifier
1kΩ
+2.5V ½-rail bias
220nF
Input
100nF
100kΩ
+
8
IC1a
–
4
Output
Input
+
IC1b
–
10µF
Output
100µF
100µF
220µF
Input
100nF
100kΩ
100kΩ
22kΩ
2
K
TL431 Ref
A
1
3
4 x AA cells
IC1 is a dual low-voltage op amp: LM358 or MPC6002
2.2kΩ
R load
10µF
Signal ground
0V star earth joined on PCB
Power ground carries distorted currents
Power ground

Fig.2. When running op-amps in single-rail the distorted power supply currents should still be kept out of the signal ground. This shows the arrangement in the Gen X-1 synthesiser. The 2.5V reference rail acts as an artificial 0V rail.

contaminated with distorted operating currents. Circuit layout is thus more important (see *Audio Out*, Jan 2017). Some power amp ICs, such as the 5-pin TDA2030, with a single negative rail/ground pins give higher distortion when used in single-rail mode because the half-wave power pulses from the lower transistor of the push-pull output stage get superimposed on the ground rail. Even with op amps, the negative supply pin should not just go to a combined signal and power ground. They should be kept separate until joined at a suitable point at the power supply (see Fig.2). Most op amps have class AB output stages and the current from the negative power rail pin can be quite distorted. (Again, this was covered in *Audio Out*, Jan 2017.)

Going off the rails

Output capacitors are needed with single-rail operation to block the necessary half-rail DC bias. A massive bonus is that they also protect the speaker and the output stage from large sustained DC currents if there is a fault. Big wet electrolytic capacitors also fail open-circuit and so DC offset protection isn't needed. Also, if the output is shorted to ground on a dual-rail amplifier the negative feedback at DC is lost. This pushes the output to go offset to one rail, causing maximum current to flow. This can result in output transistor failure even if there is no output signal present, unless current limiting is employed. With an output capacitor, DC feedback is maintained, even with a short-circuited output.

Catastrophic events, such as a full-power DC offset destroying the loudspeaker, easily happen with dual-rail systems if an output transistor goes short circuit or (with some bad designs) one power rail is lost. Fortunately, fuses and some poly-switches usually work quickly enough to protect a loudspeaker voice coil. It takes a few seconds to blow a voice coil; however, this is only true for woofers, the voice-coil wire in a tweeter is often as thin as 1A fuse wire and is therefore particularly vulnerable. In passive speakers, the tweeter is protected by the series high-pass capacitor in the crossover. In an active speaker, the tweeter may be connected directly to a power amplifier. Therefore, it's prudent to use a protection capacitor in series with the tweeter amplifier's output in an active loudspeaker. A 10µF 63V polyester capacitor often suffices (with a tweak in the crossover to compenate).

Protection racket

Complex DC protection circuits employing a relay to disconnect the output are often used in dual-rail amplifiers, such as the *Universal Speaker Protector* published in December 2016. There are distortion problems associated with dirty contacts and magnetic problems in relays, often resulting in higher distortion than with capacitors. Relays are often single-sourced components with a high failure rate.

Dual-rail systems do allow better low-frequency performance because DC coupling can be employed and an output capacitor is not needed. However, I do still occasionally use capacitors in the output of dual-rail amplifiers to provide DC protection.

Regulation

If a regulated supply is wanted, then complexity is doubled for a dual-rail system, as is the associated drop-out voltage. Tracking may also be needed, so that one rail mirrors the other. It is rare to see a dual-rail regulated power supply on power amps. John Linsley-Hood designed a ±57V one for his MOSFET design (*ETI*, August 1984) but it was more complex than the amplifier it was powering, using a total of 22 transistors! It had simultaneous shutdown if either rail was shorted, which also operated if an offset was detected, protecting the speakers. It was a popular Hart Electronics kit for many years. Quad also had a regulated supply on their single-rail 303, which was much simpler.

Testing

Single-rail amplifiers are easier to design and test with a standard bench power supply. Dual-rail *tracking* bench PSUs are rare and expensive. The cheapest is the GW Instek GPS-2303 from Rapid (90-2163) as shown in Fig.3. It has a maximum output voltage of ± 31V at 3A. This is sufficient for most power amplifier R&D work, where the full rail voltage can be applied later when the design is proved (most high-power amplifiers will still operate at half voltage). This is a master/slave design, where, if the positive rail is shorted the voltage on the negative rail is pulled down as well. Unfortunately, it doesn't do this if the negative rail is shorted. However it is fine for testing most amplifier designs since there are adjustable current limits on both rails.

LABORATORY DC POWER SUPPLY
GW INSTEK GPS-2303
CURRENT
VOLTAGE
TRACKING
MASTER
SLAVE
POWER

Fig.3. Dual-rail tracking bench power supply. Ideal for safe power-amp development. (GW-Instek GPS-2303 Rapid 90-6123).

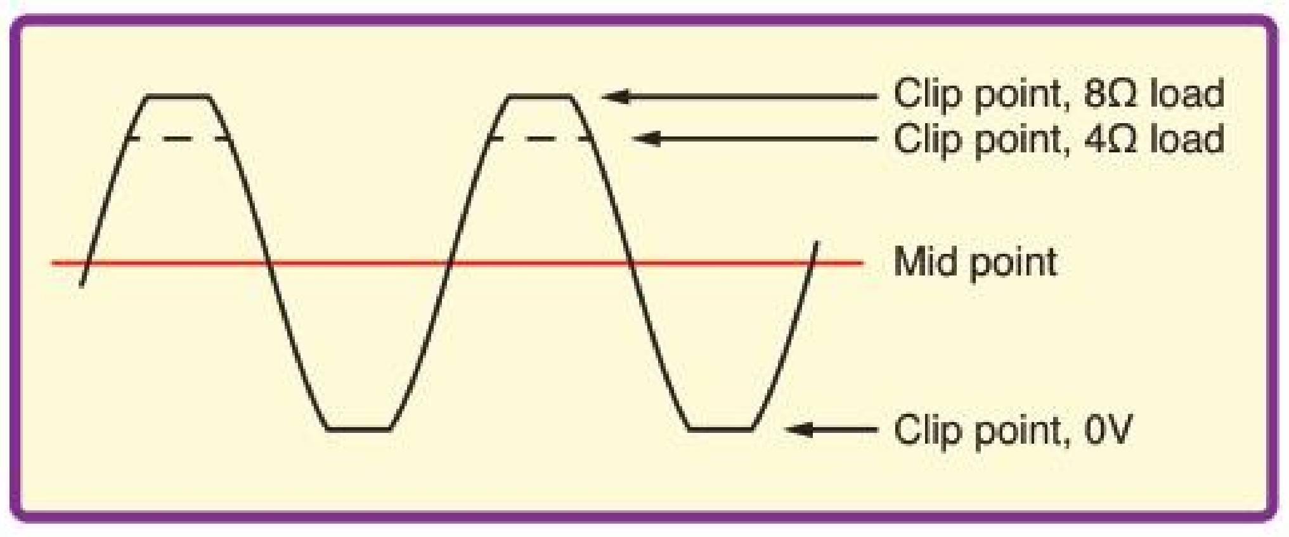

Fig.4. Asymmetrical clipping caused by power supply 'sag' in single-rail amplifier.

Shifty bias

In single-rail unregulated power supply amplifiers, the output has to be biased to half-rail voltage. Normally, this is derived from a potential divider. Supply noise can enter here unless it is properly decoupled with an RC network.

Also, with an unregulated supply, the bias point will shift with power supply variation (in a delayed manner). This results in 'speaker pumping' (slowly moving in and out) on tone-bursts. This additional low-frequency modulation is a form of distortion. It can be blocked by making the time constant of the output capacitor / speaker impedance network faster than that of the power supply. Last, note that bias point shift will also cause asymmetrical clipping (see Fig.4).

With single-rail, the bias point can only be optimised for a given power supply and loudspeaker drive unit. This is ideal for active speakers, where the amplifiers and drive units are designed as one system, but not for separate amplifiers, which have to be able to drive any loudspeaker.

Slow mains voltage fluctuations will also appear on the output, which can be seen on a 'scope when checking the noise level. These problems can be fixed by regulating the bias. This has the disadvantage that the circuit must then be operated at a specified supply voltage. For music, bias should be set for symmetrical clipping at off-load, since this will allow transients to be passed before the power supply sags. Where the signal is more continuous, as with electronic organs, theremins or sinewave inverters it's best to set for symmetrical clip at full power on load.

Dual-rail systems are self-centring and a symmetrical swing is assured under different conditions. With single-rail, a regulated power supply gives the same quality. This is one reason Quad and the 1970 *PE Gemini* used them (Alan Winstanley has kindly put a PDF of this on *Chat Zone*, and it is still a valid design).

Next month

We will continue next month in *Part 2* with a look at output capacitor power losses and negative feedback

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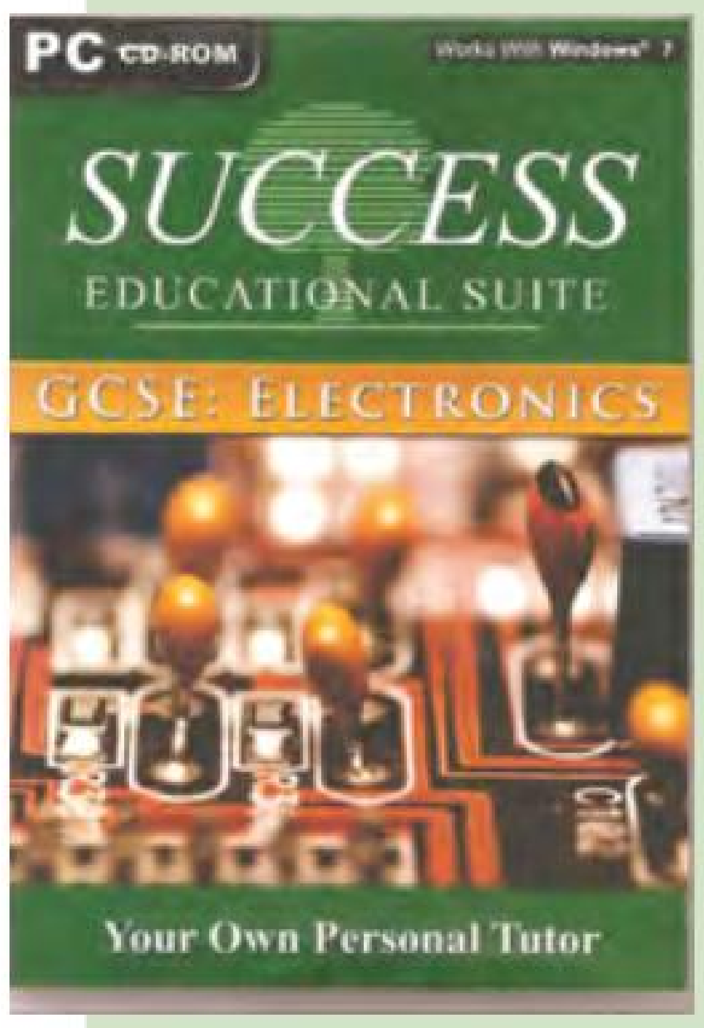

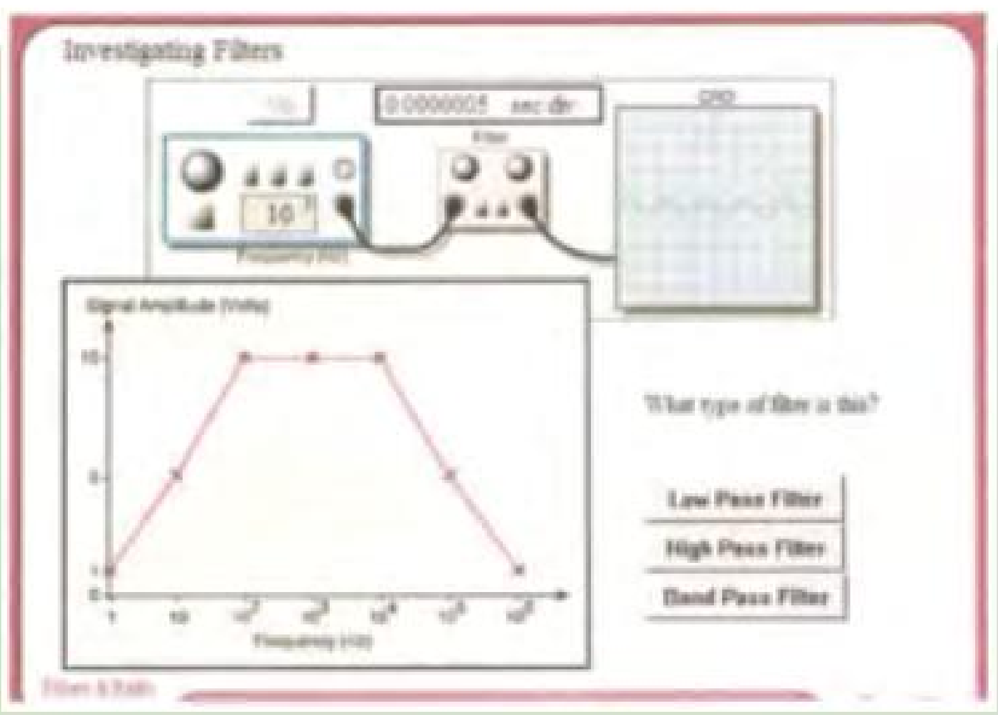

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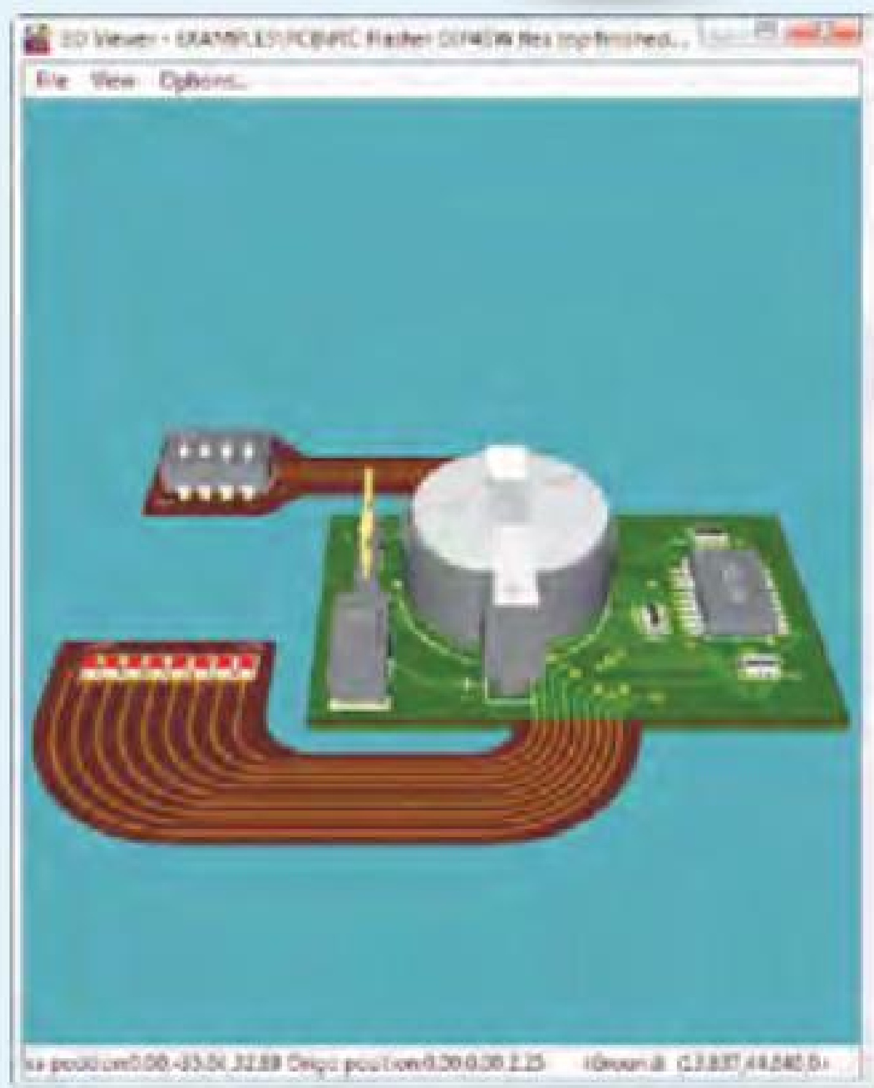

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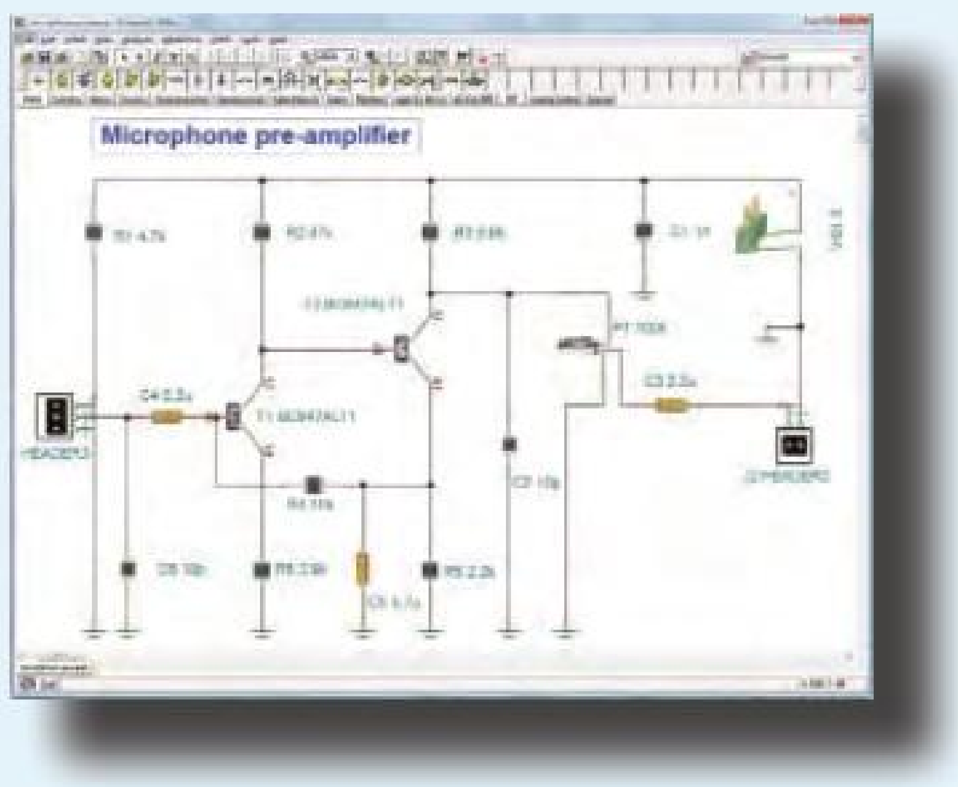

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ASSEMBLY FOR PICmicro V6

(Formerly PICtutor)

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The CD makes use of the latest simulation techniques which provide a superb tool for learning: the Virtual PICmicro microcontroller, this is a simulation tool that allows users to write and execute MPASM assembler code for the PIC16F84 microcontroller on-screen. Using this you can actually see what happens inside the PICmicro MCU as each instruction is executed, which enhances understanding.

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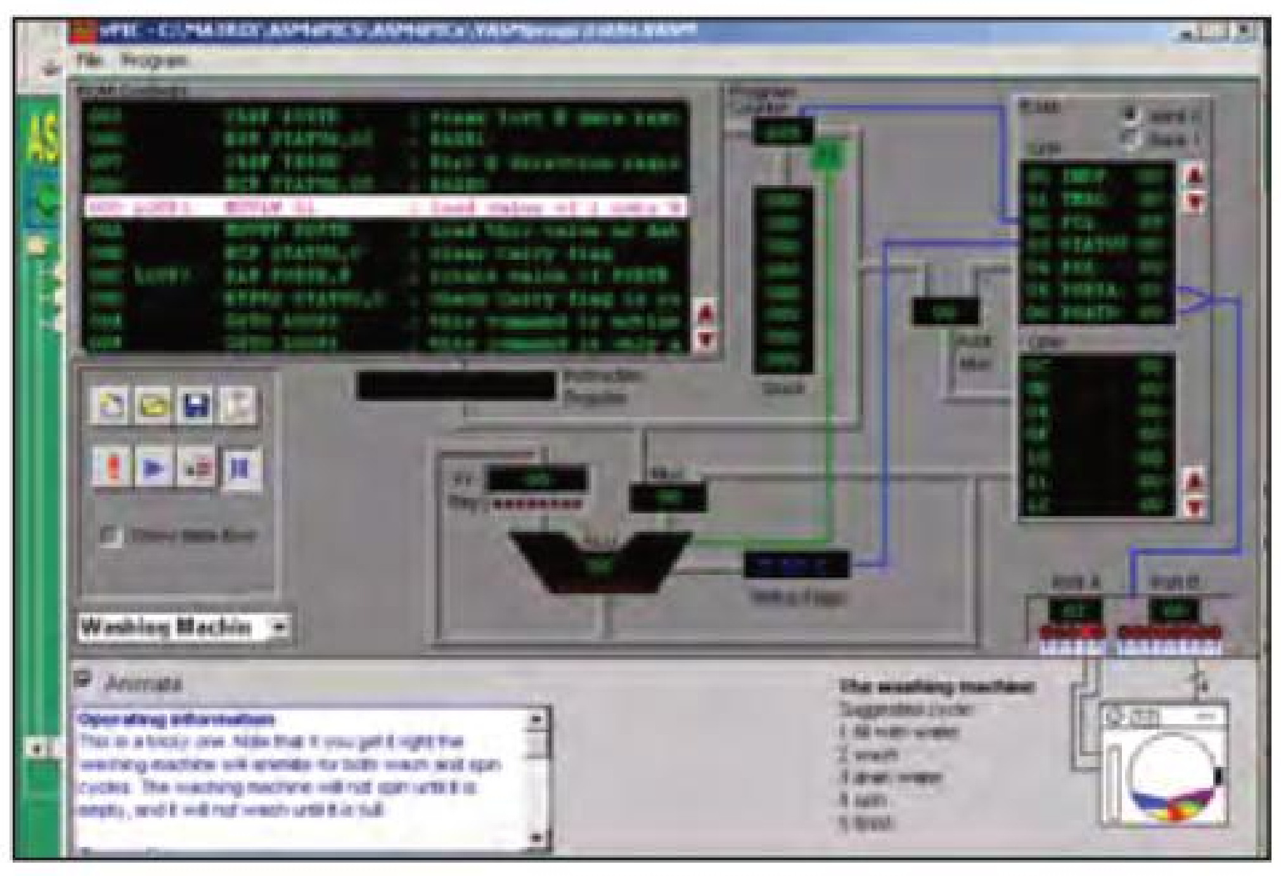

'C' FOR 16 Series PICmicro Version 5

The C for PICmicro microcontrollers CD-ROM is designed for students and professionals who need to learn how to program embedded microcontrollers in C. The CD-ROM contains a course as well as all the software tools needed to create Hex code for a wide range of PICmicro devices – including a full C compiler for a wide range of PICmicro devices.

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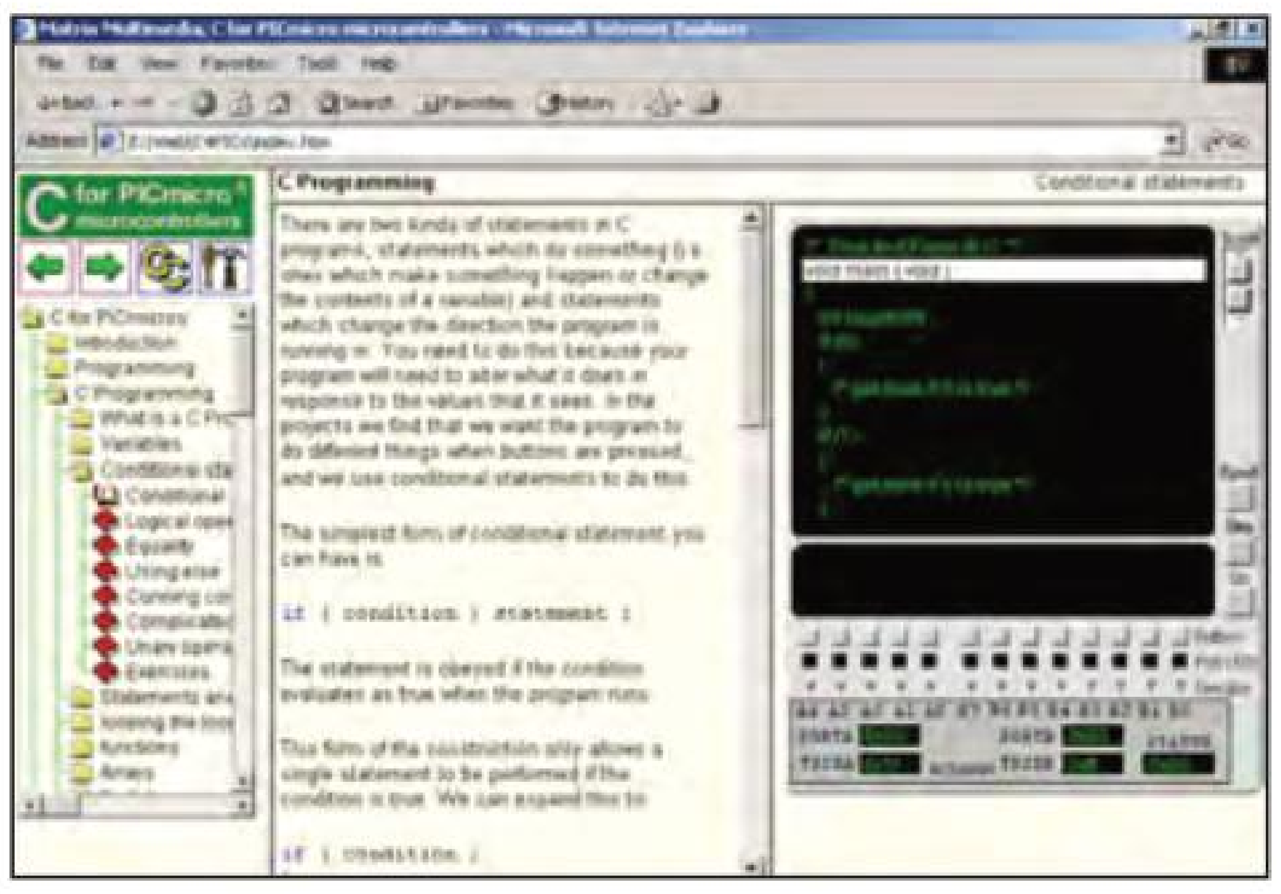

This software will run on Windows XP or later operating systems

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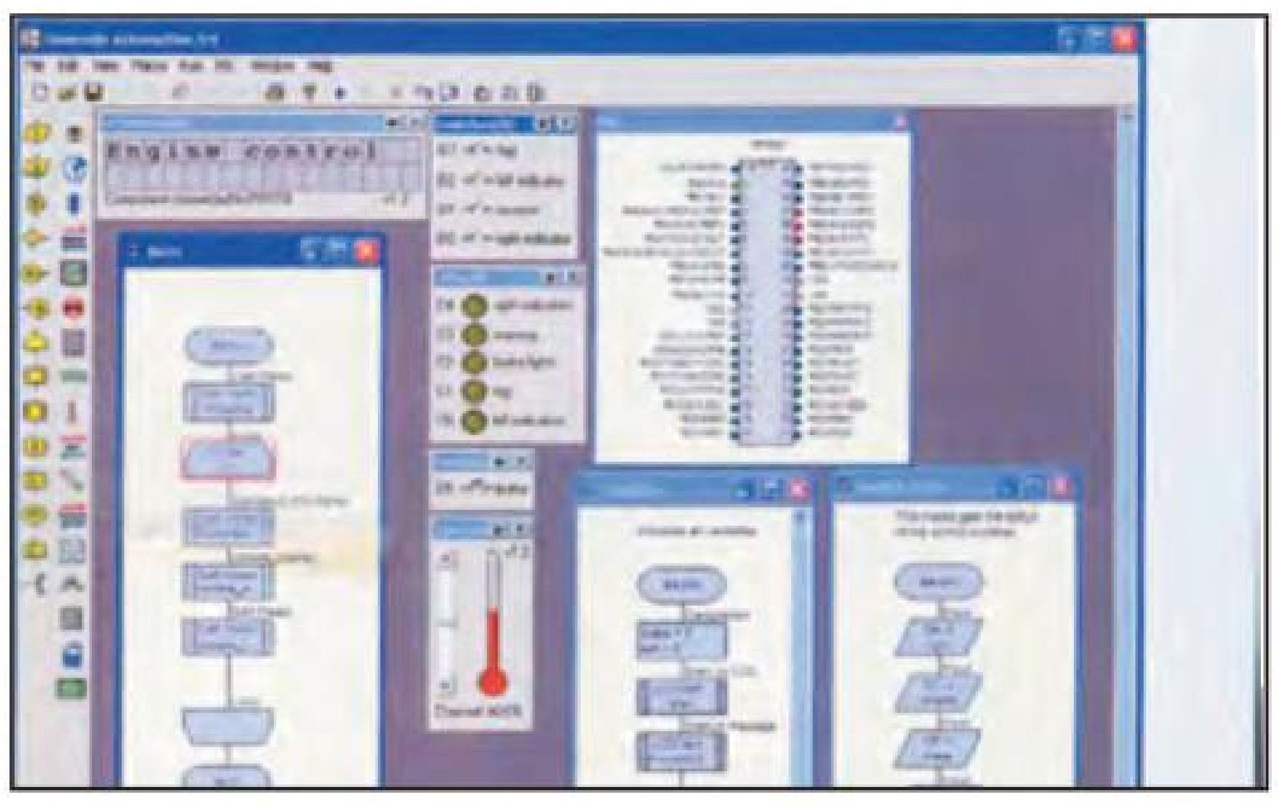

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USING PIC MICROCONTROLLERS A PRACTICAL INTRODUCTION

This *Teach-In* series of articles was originally published in *EPE* in 2008 and, following demand from readers, has now been collected together in the *Electronics Teach-In 2* CD-ROM.

The series is aimed at those using PIC microcontrollers for the first time. Each part of the series includes breadboard layouts to aid understanding and a simple programmer project is provided.

Also included are 29 *PIC N' Mix* articles, also republished from *EPE*. These provide a host of practical programming and interfacing information, mainly for those that have already got to grips with using PIC microcontrollers. An extra four part beginners guide to using the C programing language for PIC microcontrollers is also included.

The CD-ROM also contains all of the software for the *Teach-In 2* series and *PIC N' Mix* articles, plus a range of items from Microchip – the manufacturers of the PIC microcontrollers. The material has been compiled by Wimborne Publishing Ltd. with the assistance of Microchip Technology Inc.

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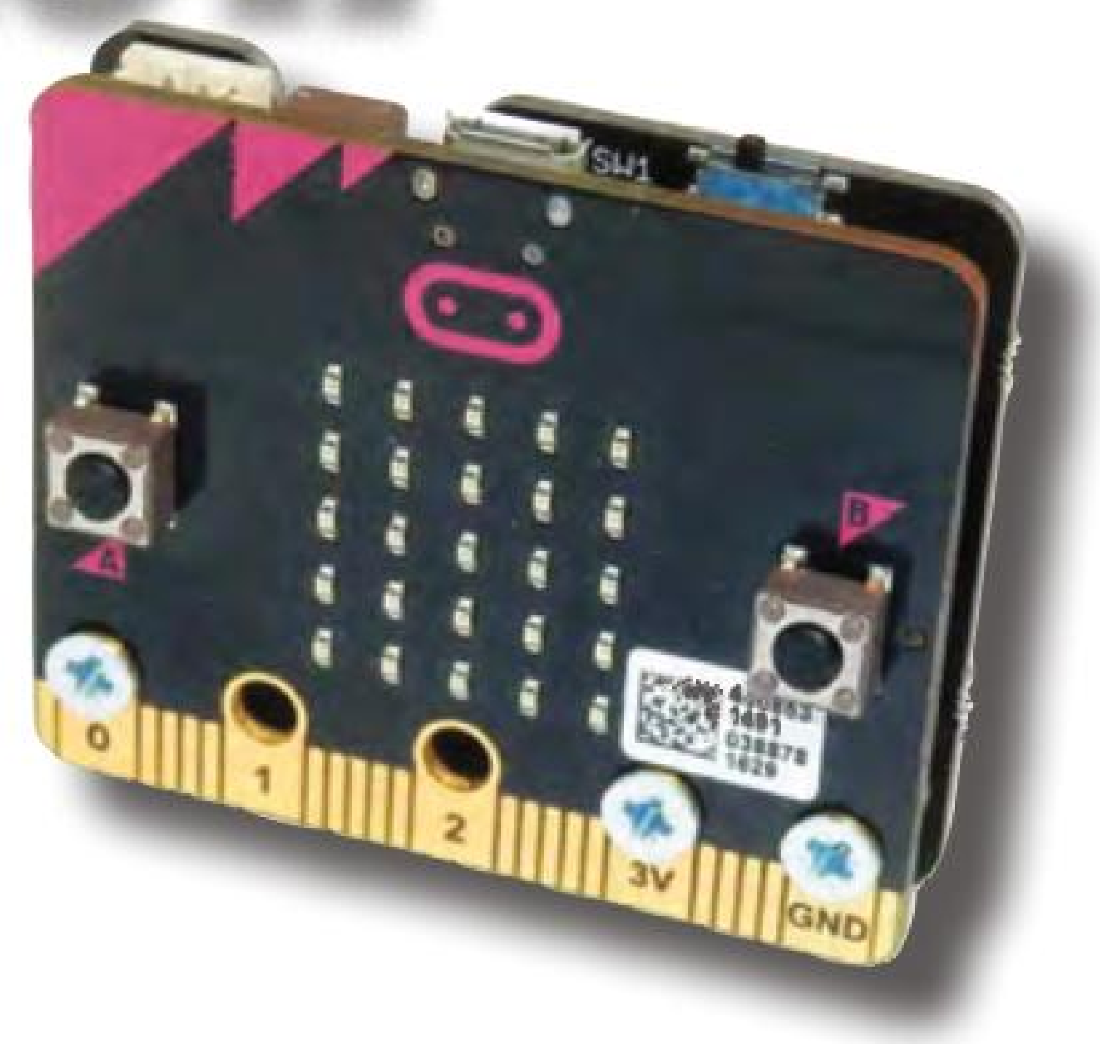
Teach-In 2017

Introducing the BBC micro:bit



NEW

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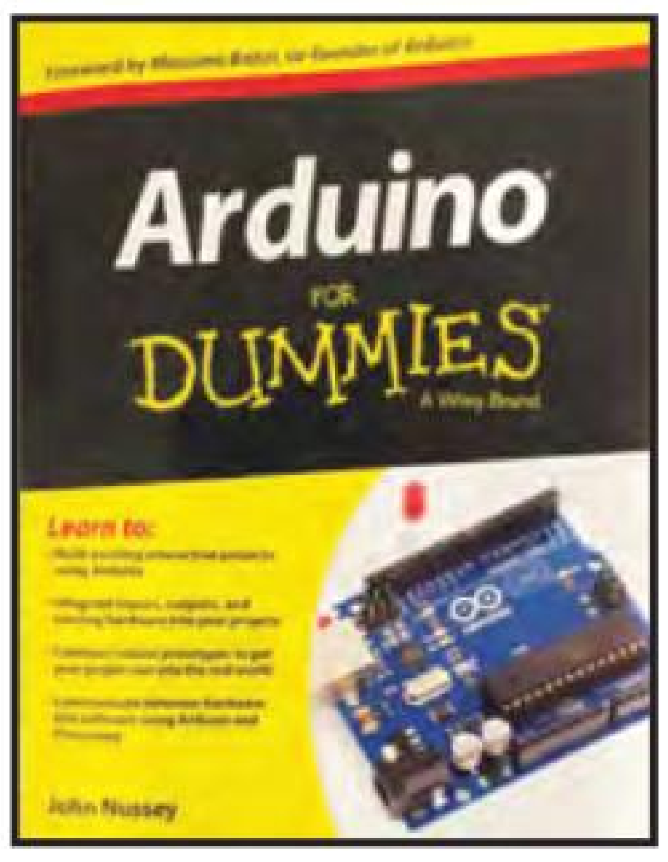
Teach-In 2016

Exploring the Arduino



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John Nussey

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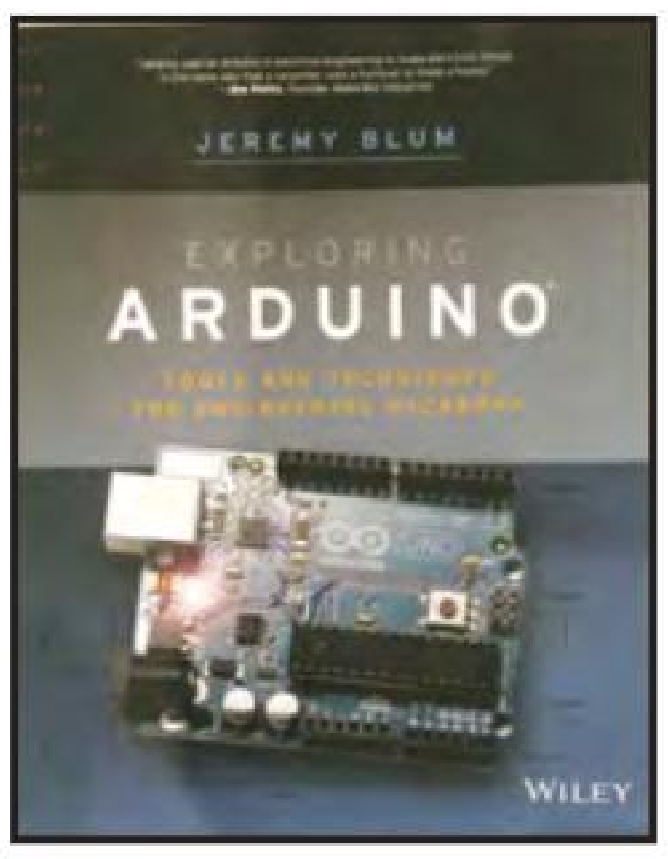

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Jeremy Blum

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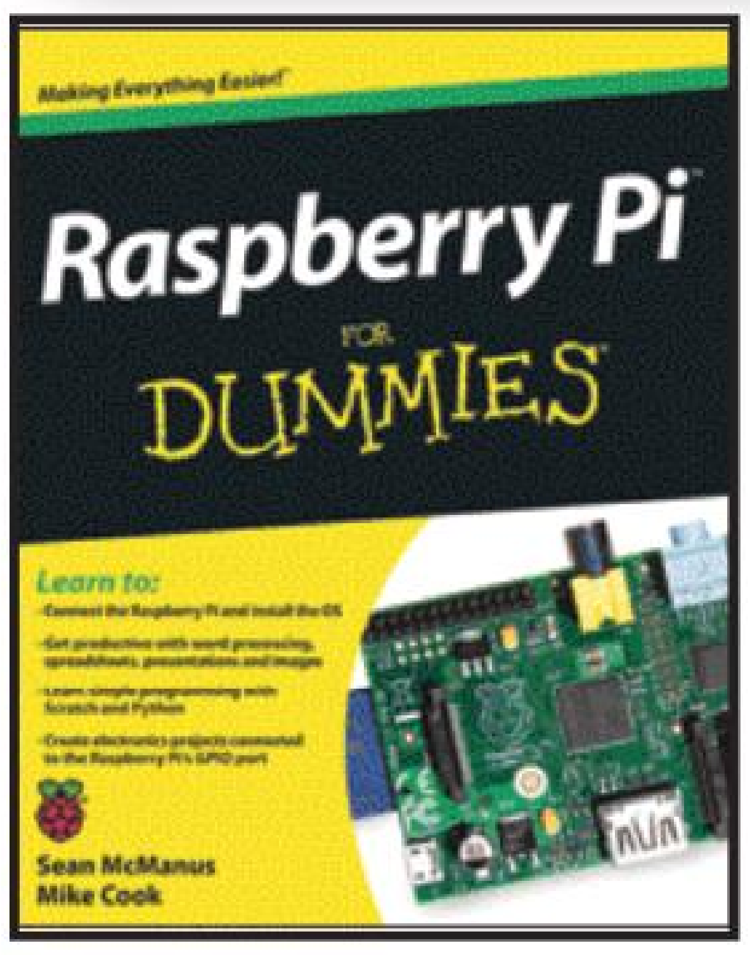

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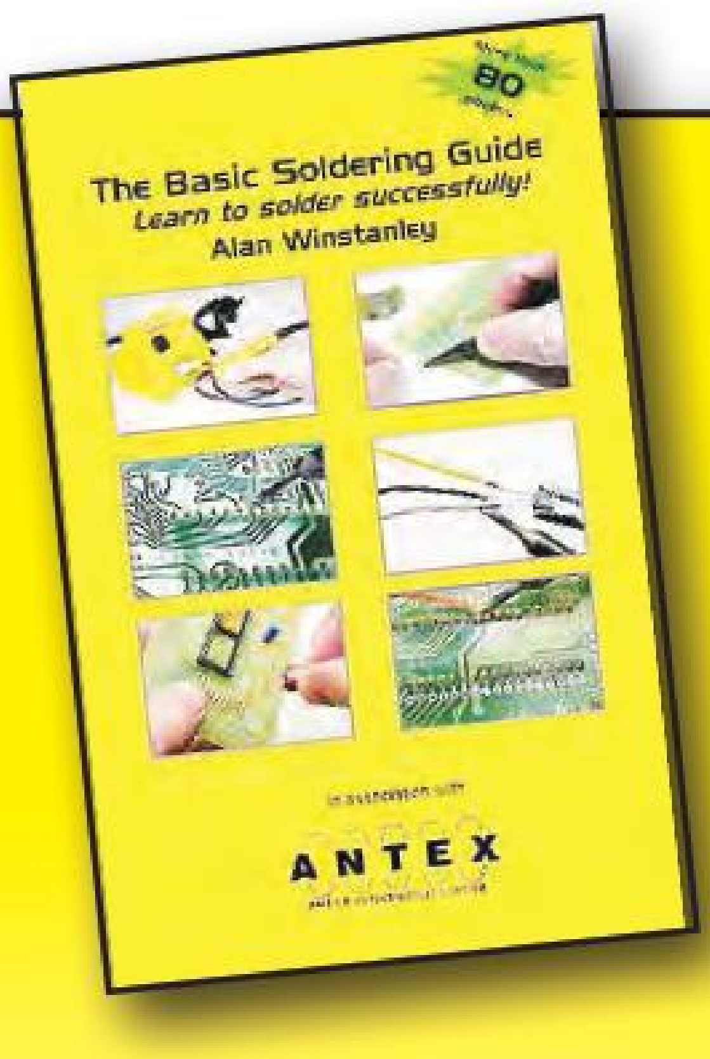

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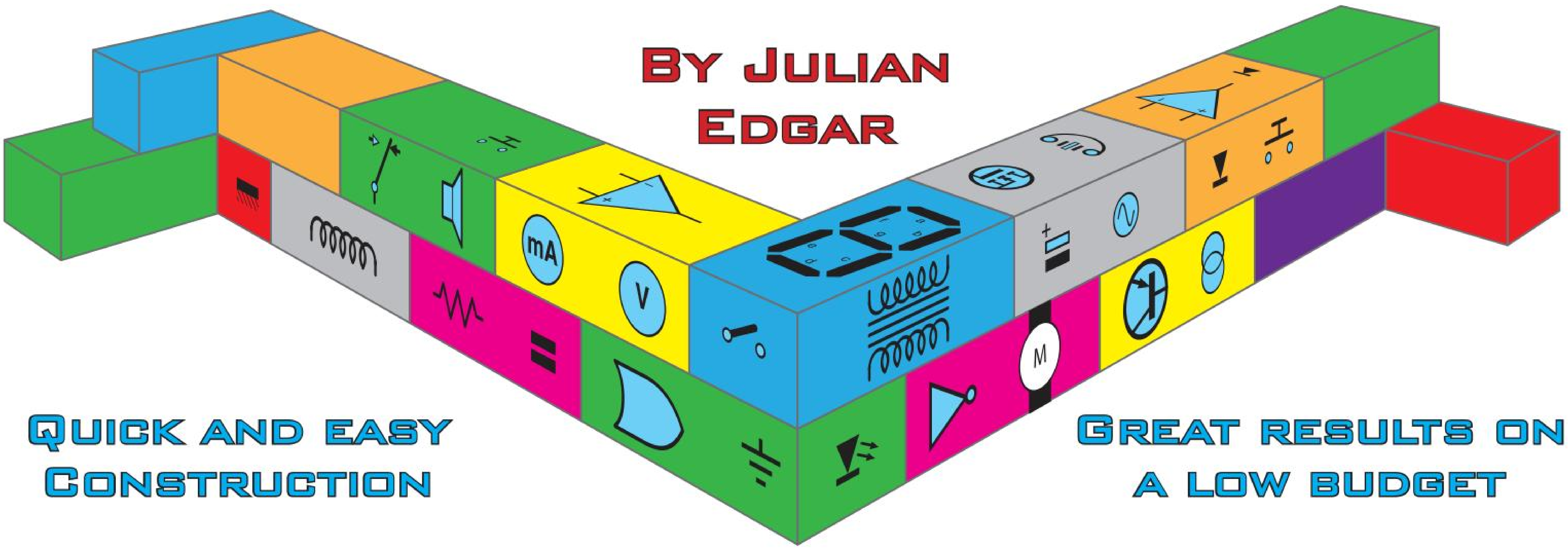

BY JULIAN EDGAR

QUICK AND EASY CONSTRUCTION

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LED VU METER

Large complex projects are fun, but they take time and can be expensive. Sometimes you just want a quick result at low cost. That's where this series of *Electronic Building Blocks* fits in. We use 'cheap as chips' components bought online to get you where you want to be... FAST! They represent the best value we can find in today's electronics marketplace!

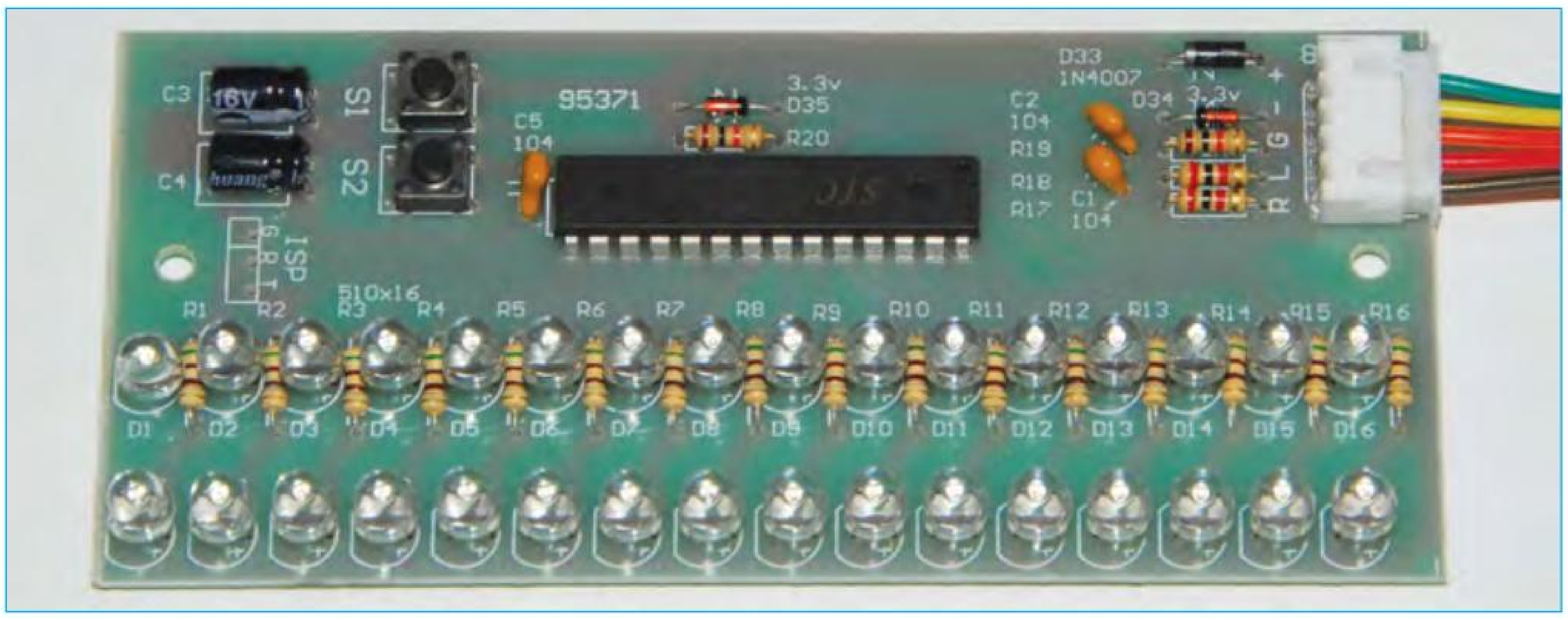


Fig.1. This fully pre-built module uses two rows of 16 LEDs to show audio levels.

The trouble with many home-brewed amplifiers (mine included!) is that they tend to end up looking like a black box with an on/off switch. Sure, the innards might be great to look at, but positioned on a shelf, it's just another black box. But now here's a chance to add some bling to your next amplifier design using this versatile LED display. It's an easy way to add an eye-catching and useful LED display. Simply buy the 'MCU Adjustable Display Pattern LED VU Meter Level Indicator 16 LED Dual Channel' for just £4 (including delivery – eBay no. 253073245255)!

What do you get for your money?...

What you receive is a fully-built module that uses two rows of LEDs. The PCB is 50 × 110mm with two mounting holes spaced 100mm apart. Green LEDs are used, with each row containing 16 LEDs. Also on the board is a microcontroller, a few additional components and two pushbuttons. Wiring comprises line-level input signals (left, right and common) and a DC power feed. The board will operate on 8-12V, and the input signal amplitude needs to be within the range of 300mV to 5V (so don't connect it straight to the amplifier's speaker outputs!).

...and how do you use it?

It's the two buttons and micro that make this board so useful. Each button has two modes – short press and long press.

The first function of Switch 1 (S1 – the switches are labelled on the board) adjusts the input signal gain. So if the LED display lights up only the first few LEDs of the bar graphs during audio playback, you can increase the gain by multiple presses of this button. A long press of S2 changes the function of S1, allowing it to set the LED brightness. The selected LED brightness is indicated not only by the brightness of the LEDs but also by the lower display becoming a bar graph that shows the selected level. The maximum brightness is very bright indeed (positively dazzling) and the minimum brightness perfectly suitable for semi-darkness.

Table 1: LED VU meter display modes and configurations

Mode	Display configuration
Mode 1	Conventional bar graph display, with higher input amplitude equalling more LEDs lit
Mode 2	As Mode 1, but with the peaks indicated by a single far right-hand LED staying illuminated
Mode 3	The far left-hand LED remains lit, and a group of three LEDs move to indicate the amplitude
Mode 4	As Mode 3, but with peak levels indicated by a single LED staying illuminated
Mode 5	The illuminated bar graph is centred in the display, with higher amplitudes indicated by more left and right LEDs lit
Mode 6	The far left-hand LED remains lit, with a train of illuminated LEDs racing across the display to the far end
Mode 7	Single LEDs racing across to the right, like individual ants!

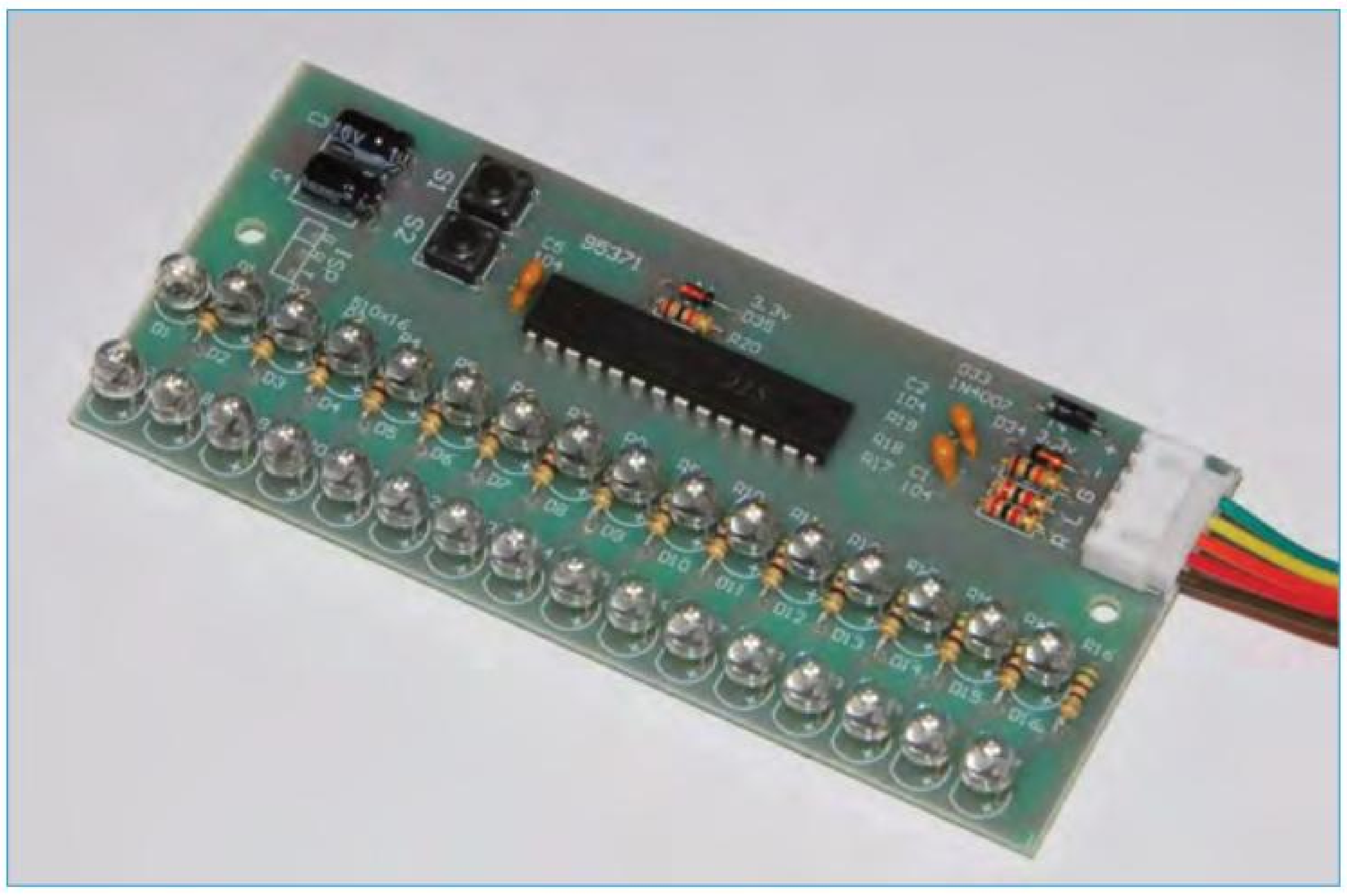


Fig.2. The module has no less than seven different display modes, accessed by the push of a button. Line level input signals are used and power is 8-12V DC.

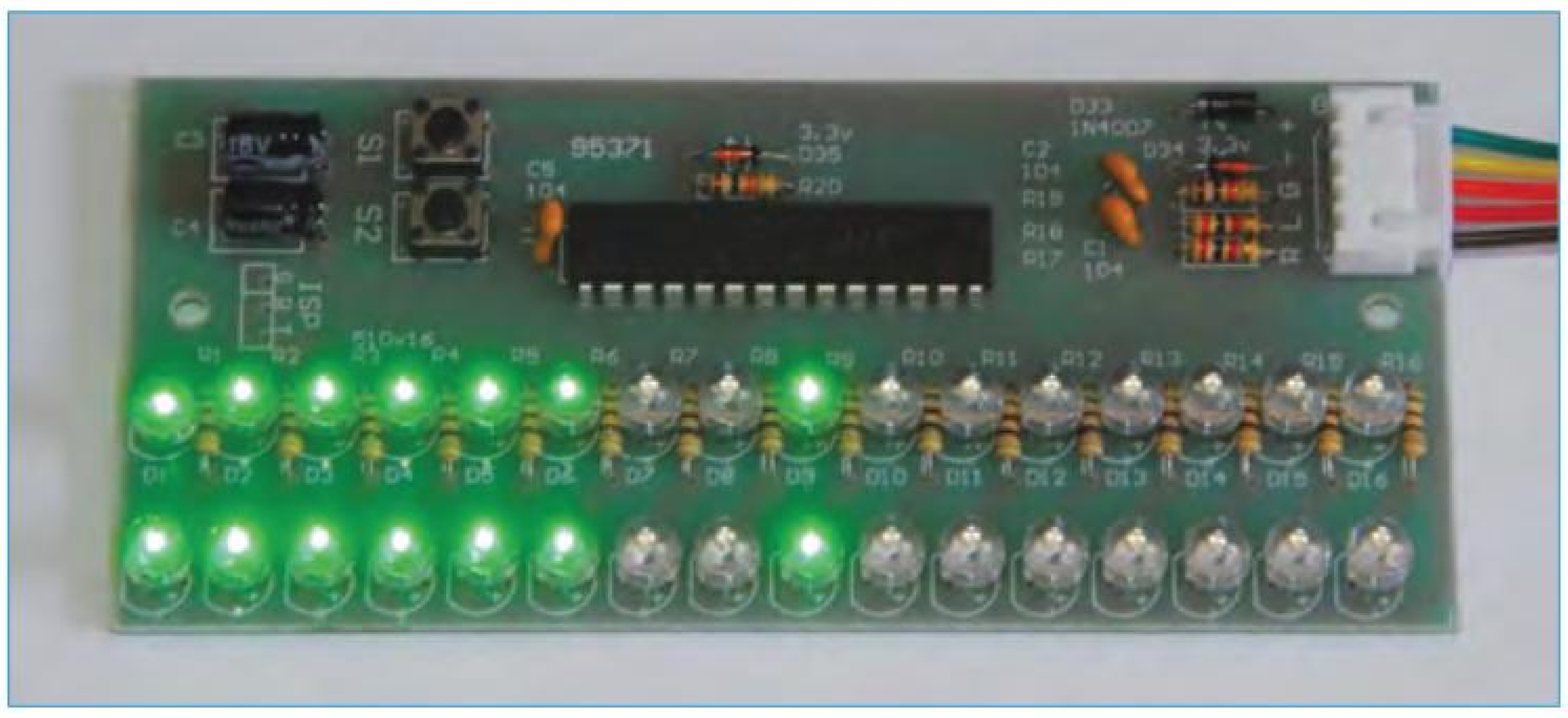


Fig.3. One of the display modes comprises bar graphs with 'peak hold' LEDs.

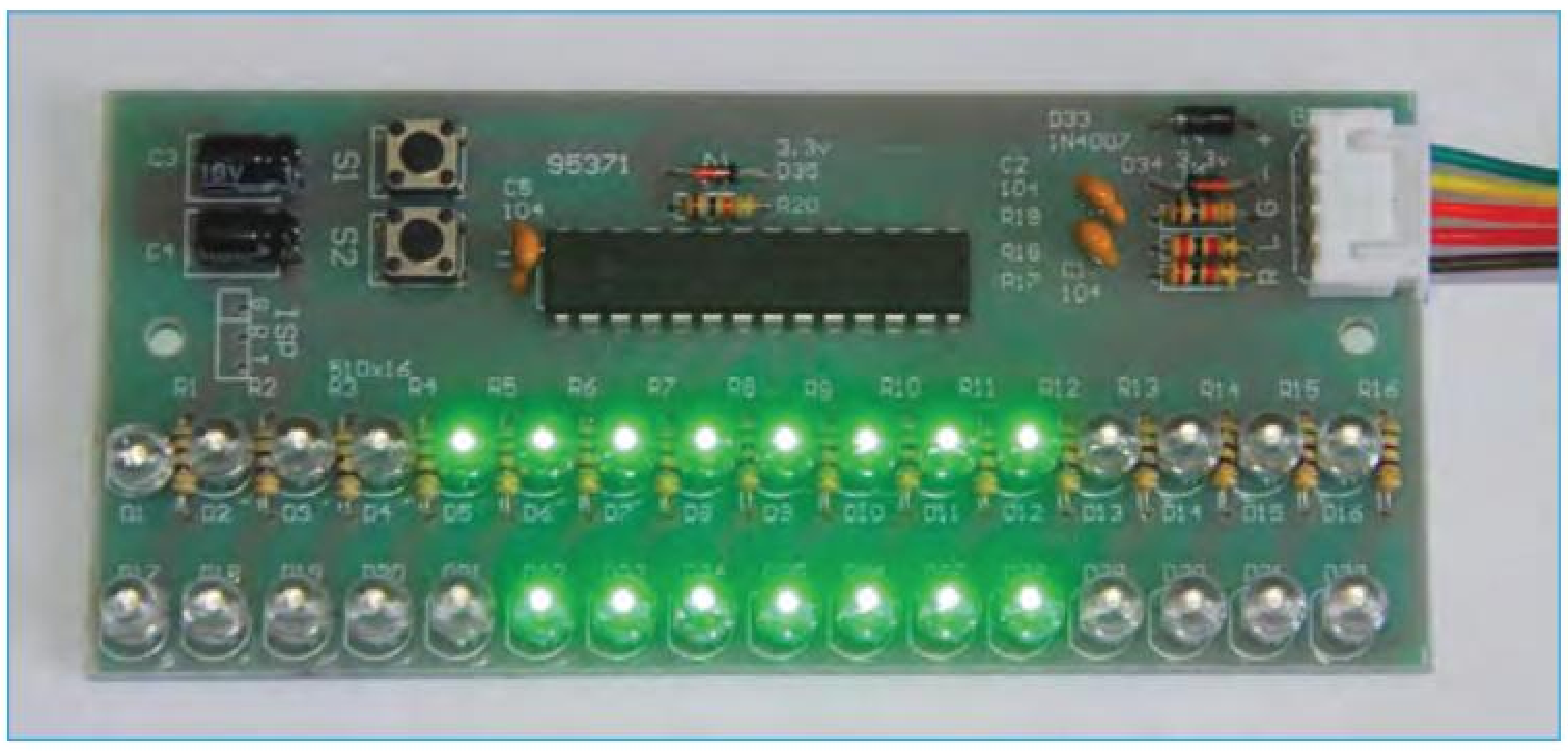
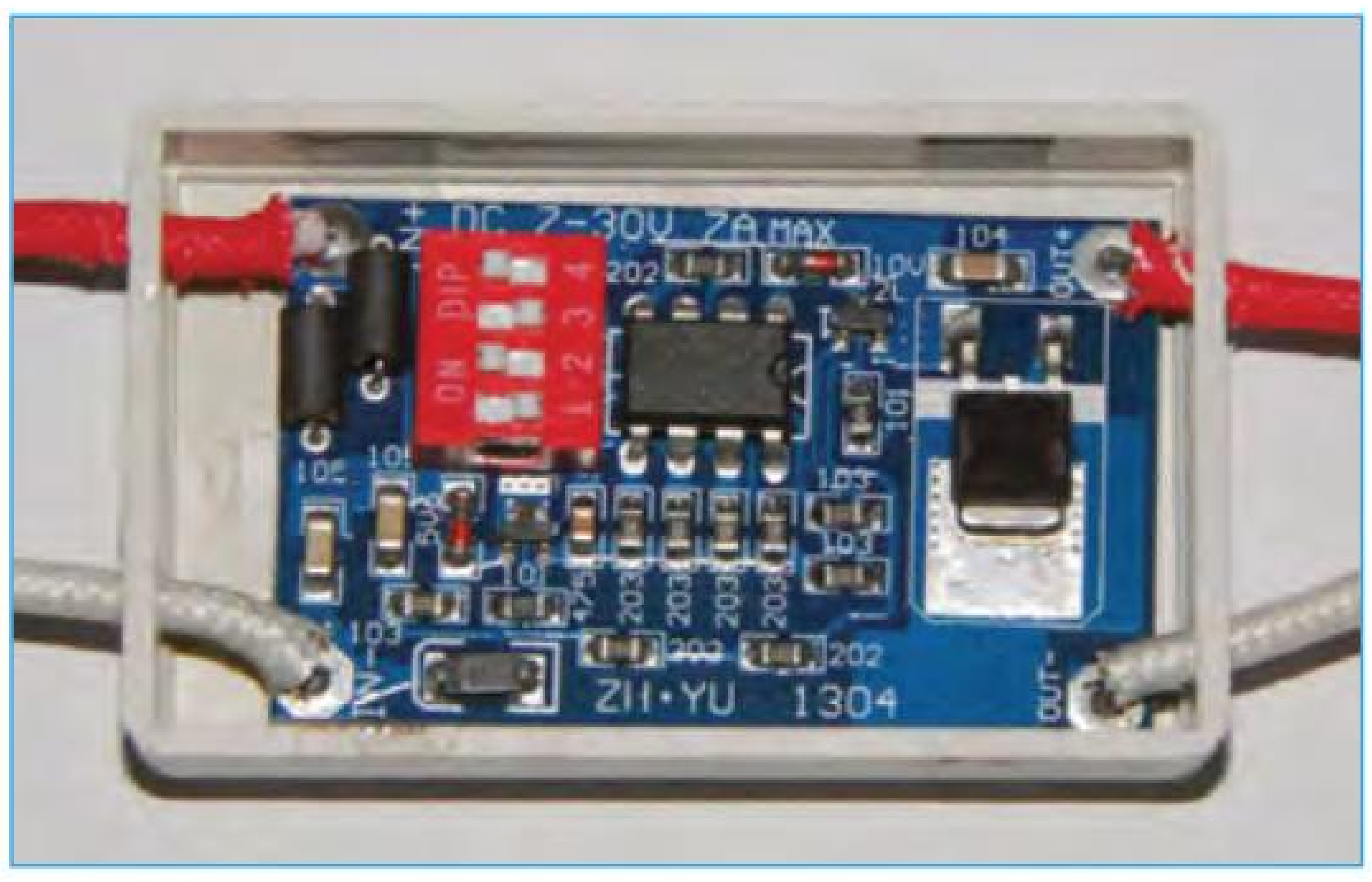


Fig.4. This display mode centres the displays, with the bar graphs extending further left and right to show greater levels.

Note that the selected gain and brightness levels are retained, even with power off.

Display modes

S2 activates the functions that make this module such a good buy. In addition to a normal VU bar graph display, there are another six display options. Some are rather hard to describe, but in brief they look as described in Table 1. (Note that the behaviour of both channels is identical, so only one channel is described in the table on the previous page.) Modes 6 and 7 don't really show audio levels as such, but they are fun to watch – rest assured, if you want to find an exciting display to jazz up your amplifier, you've come to the right place!



Next time

In my next column I'll be looking at a high-current flasher.

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All prices include VAT and postage and packing. Add £2 per board for airmail outside of Europe. Remittances should be sent to **The PCB Service, Everyday Practical Electronics, Wimborne Publishing Ltd., 113 Lynwood Drive, Merley, Wimborne, Dorset BH21 1UU. Tel: 01202 880299; Fax 01202 843233; Email: orders@epemag.wimborne.co.uk. On-line Shop: www.epemag.com**. Cheques should be crossed and made payable to *Everyday Practical Electronics* **(Payment in £ sterling only)**.

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CRICKLEWOOD ELECTRONICS 33
EPTSOFT Ltd 33
ESR ELECTRONIC COMPONENTS 6
HAMMOND ELECTRONICS Ltd 9
iCSAT 57
JPG ELECTRONICS 72
KCS . . . . . Cover (iv)
LASER BUSINESS SYSTEMS 56
MICROCHIP . . . . . Cover (iii), 10 & 49
PEAK ELECTRONIC DESIGN . . . . . Cover (ii)
PICO TECHNOLOGY 69
POLABS D.O.O. 57
QUASAR ELECTRONICS 2/3
RAPID ELECTRONICS 18
STEWART OF READING 33
TAG-CONNECT 57
TRINITY 37

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Next Month

FEBRUARY '18 ISSUE ON SALE 4 JANUARY 2018

GPS-synchronised Analogue Clock Driver

Traditional clocks (with hands) are fairly accurate – but every now and then you have to take them off the wall for adjustment so they show the 'real' time. Build this *GPS Analogue Clock Driver* and your clock will automatically adjust itself so it is always 100% spot on – even taking account of daylight saving!

SC200 audio amplifier – Part 2

In the January issue we introduced this completely new amplifier circuit, which uses easy-to-solder through-hole components. Next month, we're presenting the construction details.

DC speed controller: 12 to 60V at up to 40A – Part 2

Continuing on from January, here are the assembly and setup details for our powerful DC motor controller. Remember – if you want a design with bags of power then this is the project for you. It can run with a DC supply from 12V to 60V, delivering currents up to a phenomenal 40A

DC Motor Controller

Teach-In 2018 – Part 5

Next month's *Teach-in 2018* will look at inductors, resonant circuits and quartz crystals. Our practical project will feature a useful crystal checker that can also be used as a handy calibration source. We will also be introducing Q-measurement and the use of a dip meter for checking tuned circuits.

PLUS!

All your favourite regular columns from *Audio Out* and *Circuit Surgery* to *PIC n' Mix* and *Net Work*.

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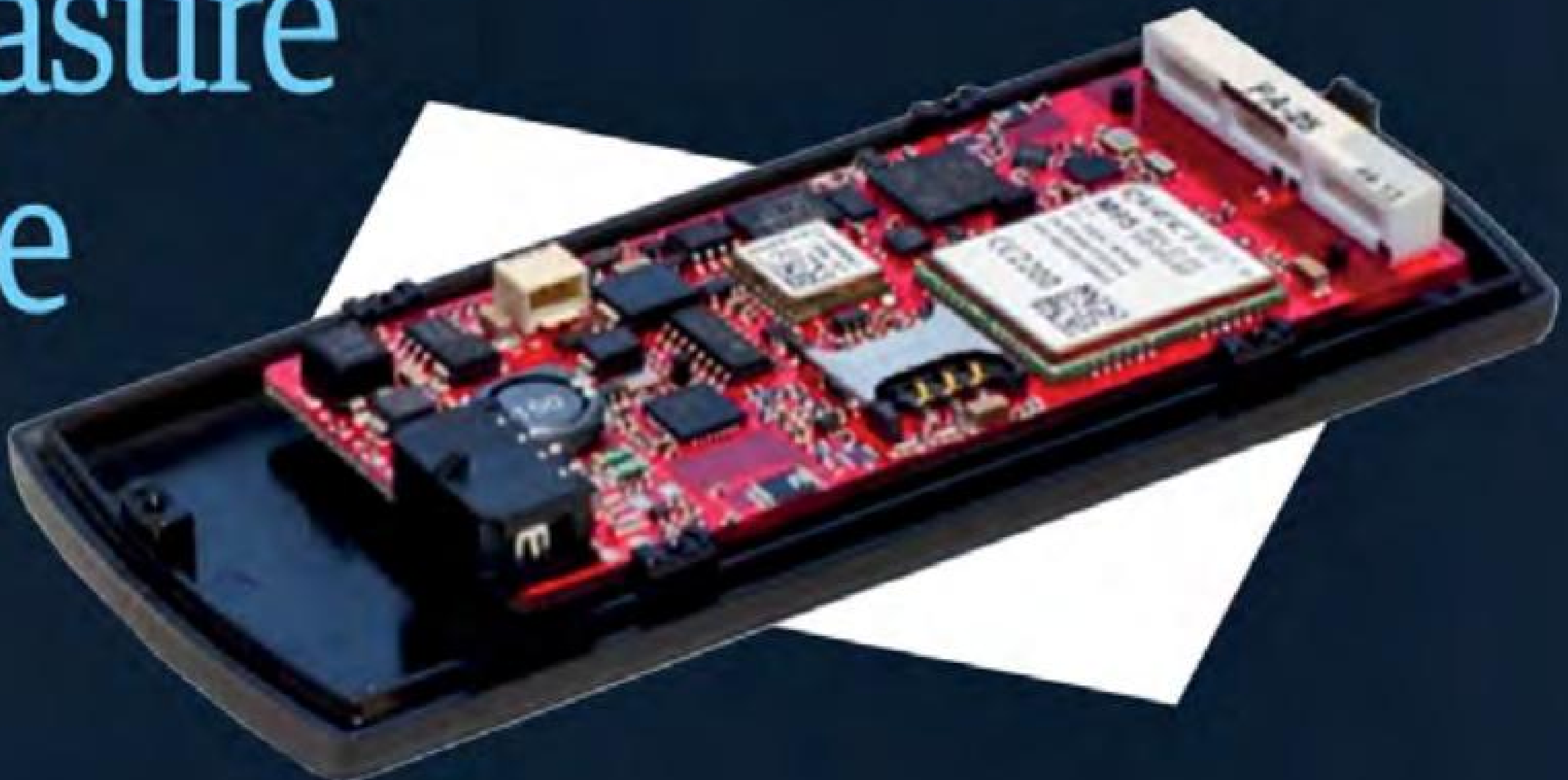

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